MICROMACHINING OF GaN USING PHOTOELECTROCHEMICAL ETCHING

Abstract

by

Bo Yang

GaN and related materials have excellent electrical, optical and chemical properties for a wide range of applications including high power, high temperature electronics, LEDs and lasers, sensors, and MEMS in harsh environments. Due to its high chemical stability, GaN is resistant to common etchants, and poses a challenge for fabrication. Micromachining techniques for GaN and related materials based on photoelectrochemical (PEC) etching, which overcomes the chemical stability of GaN by photogenerating electron-hole pairs in GaN during etching, is developed and demonstrated. Although many excellent results have been obtained with dry etching techniques, a viable photoelectrochemical etching (PEC) approach is still attractive since PEC etching is expected to result in less damage as well as offering unique characteristics such as dopant-selective and bandgap-selective etching.

In this study, PEC etching of GaN and related materials is demonstrated, the mechanism of PEC etching of GaN is investigated, and a two-step etching model for PEC etching of GaN is developed. In addition, the relationships between etch rate, etched surface morphology and the incident light intensity and electrolyte
concentration have been studied. Control of the etched surface morphology, which is critical for many device applications, has been investigated and demonstrated. Prior reports of PEC etching have shown that rough surfaces, related to the high density of dislocations in the material, are typically attained. Through study of the effect of electrolyte concentration, light intensity, and applied voltage bias, conditions that produce a very smooth surface with root-mean-square surface roughness of approximately 0.5 nm have been identified. Lateral PEC etching of GaN by several approaches, including through-wafer (backside) illumination and bias assisted etching, has been investigated for the fabrication of deeply undercut structures. Use of an applied voltage bias was found to enhance the lateral PEC etching of GaN in front-side illuminated PEC etching, allowing the fabrication of suspended Ti cantilevers. Fabrication of SiO$_2$ and AlGaN (dielectric and semiconductor) membranes has also been demonstrated. These processes are promising for fabrication of novel sensors and MEMS devices. Enabled by the etching techniques demonstrated in this research work, an inline transmissive microwave power sensor has been designed and simulated. It offers several advantages over conventional power sensors by allowing it to be easily integrated with low-loss coplanar transmission lines and GaN-based transistors. Thermal and electromagnetic designs and simulations of the sensor have been performed, and the relationships between its structure and performance, including the responsivity, response time (thermal time constant) and noise equivalent power have been established.
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ACKNOWLEDGMENTS

I would like to acknowledge all my loving friends at Notre Dame. I would like to thank my committee members, Dr. Hall, Dr. Kosel, Dr. Xing and Dr. Bernstein for their reading and suggestions. I would also like to thank my advisor, Dr. Fay, without whom this work would not have been possible. Finally, I would like to thank my parents, my brothers and my sisters.
CHAPTER I

INTRODUCTION AND BACKGROUND

1.1 Properties and applications of GaN and related wide bandgap materials

Recent results in many laboratories have demonstrated the promise of GaN and related wide bandgap materials such as AlGaN and InGaN for applications in high power and high temperature electronics [1-6], high-power high electron mobility transistors [7-11], blue, violet and ultraviolet light-emitting diodes and laser diodes [12-15], and short-wavelength photodetectors [16-18].

TABLE 1.1 SELECTED MATERIAL PROPERTIES OF WURTZITE GaN [19].

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandgap energy</td>
<td>$E_g(300 \text{ K}) = 3.42 \text{ eV}$  $E_g(4 \text{ K}) = 3.505 \text{ eV}$</td>
</tr>
<tr>
<td>Temperature coefficient</td>
<td>$dE_g/dT = -6.0 \times 10^{-4} \text{ eV/K}$</td>
</tr>
<tr>
<td>Pressure coefficient</td>
<td>$dE_g/dP = 4.2 \times 10^{-3} \text{ eV/Kbar}$</td>
</tr>
<tr>
<td>Lattice constant</td>
<td>$a = 3.189 \text{ Å}$  $c = 5.185 \text{ Å}$</td>
</tr>
<tr>
<td>Thermal expansion</td>
<td>$\Delta a/a = 5.59 \times 10^{-6} /\text{K}$  $\Delta c/c = 3.17 \times 10^{-6} /\text{K}$</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>$k = 1.3 \text{ W/cm-K}$</td>
</tr>
<tr>
<td>Index of refraction</td>
<td>$n(1 \text{ eV}) = 2.35$  $n(3.42 \text{ eV}) = 2.85$</td>
</tr>
<tr>
<td>Dielectric constant</td>
<td>$\varepsilon_r = 10.4$  $\varepsilon_\infty = 5.47$</td>
</tr>
<tr>
<td>Electron effective mass</td>
<td>$m_e = 0.22 m_0$</td>
</tr>
</tbody>
</table>
Some selected basic material properties of hexagonal wurtzite GaN are listed in Table 1. The crystal structure and energy band structure are shown in Fig. 1.1 and Fig. 1.2. Compared with the properties of group IV and II-VI wide bandgap materials, GaN has outstanding thermal, electronic and optical properties for these applications [19]. For example, GaN has a relatively high thermal conductivity of approximately 1.3 W/cm-K. For comparison, this is about three times than that of GaAs. In addition, GaN has a much higher breakdown electric field of $3 \times 10^6$ V/cm, compared to $4 \times 10^5$ V/cm for GaAs.

![Fig. 1.1 The wurtzite crystal structure of GaN, showing the conventions used to discuss its polarity. The size of the spheres indicates the ionic radius; note that in diagrams which use covalent radii, the gallium atoms are bigger than the nitrogen atoms [20].](image)
Fig. 1.2 Energy band structure for wurtzite GaN [21].

The wide bandgap of GaN makes it suitable for use in high temperature electronics by reducing thermal generation of electron-hole pairs dramatically, compared to more conventional materials like GaAs. Other properties of this material also contribute to its usefulness for electronics. For example, Shur et al. demonstrated high drift velocities in GaN as shown in Figure 1.3 [22]. Figure 1.3(a) compares the drift velocities for wurtzite GaN, α-SiC, Si and GaAs at room temperature, while Figure 1.3(b) shows the velocity-field characteristics of wurtzite GaN at different temperatures. These curves highlight the advantages of GaN, especially at high temperature. At room temperature, the saturation drift velocity and the breakdown field are much higher for GaN than GaAs, Si, or SiC. Furthermore, with increasing temperature, the decrease in carrier velocity is fairly modest for GaN, as seen in Figure 1.3(b). In addition, the electron mobility of wurtzite GaN at room temperature
decreases rather little with doping, compared with other materials such as GaAs [22]. So, the introduction of donor impurities should not depress the performance of devices as much as is observed in other material systems.

Fig. 1.3 (a) Electron drift velocity in GaN, SiC, and GaAs at 300 K; (b) electron drift velocity of GaN at 300 K, 500 K and 750 K. [22]

The wide bandgaps of the nitride materials, their excellent transport properties outlined above, and the availability of heterostructures (e.g., GaN/AlGaN, GaN/InGaN) make them ideal candidates for high mobility, high power and high temperature applications [23]. In the past few years a wide range of devices have been reported, including high electron mobility effect transistors (HEMTs), heterojunction bipolar transistors (HBTs), bipolar junction transistors (BJTs), Schottky and p-i-n rectifiers, and metal-oxide-semiconductor field effect transistors (MOSFETs) [24, 25]. The historical progress of AlGaN/GaN HEMTs in power
density is shown in Fig. 1.4(a) [26], and their performances are compared with Si, GaAs and SiC based devices in Fig. 1.4(b) [27]. The first AlGaN/GaN high electron mobility transistors (HEMTs) were demonstrated by Khan et al. in 1994 [28]. As of this writing, AlGaN/GaN HEMTs and amplifiers have exhibited output power densities as high as 30 W/mm [8]. Heterojunction bipolar transistors (HBTs) based on GaN/AlGaN heterostructures have also recently been demonstrated [29, 30]. In this device, the current flows vertically through the device structure, which improves thermal dissipation and provides the possibility of even larger power-handling capability.

![Graph showing power density of AlGaN/GaN HEMTs versus year](image1)

![Graph showing performance of GaN/AlGaN-based power transistors](image2)

Fig. 1.4 (a) Historical progress of GaN transistor technology: power density of AlGaN/GaN HEMTs versus year [26]; (b) Performance of GaN/AlGaN-based power transistors as compared to GaAs-, Si- and SiC-based devices [27].
In optoelectronics, ultra-bright LEDs made of GaN-based materials, which fill the void in the optoelectronic spectrum from green to ultraviolet, have already reached the commercial stage. The importance of these achievements can be well understood with the chromaticity diagram, as shown in Fig. 1.5 [31, 32]. A true full-color display can be produced with the combination of pure green, blue (2 and 3 in Fig. 1.5) and red (1 in Fig. 1.5) light sources which covers a larger area than the NTSC television standard. These LEDs devices are more efficient than incandescent tungsten-filament lamps, and the improvement in quality of GaN materials obtained by both metalorganic molecular beam epitaxy (MOMBE) and metalorganic chemical
vapor deposition (MOCVD) leads to long life times [33]. With a shorter wavelength than red or green lasers, the blue GaN laser provides an even more effective way to store information on optical disks by increasing capacity [34]. In summary, the results in many laboratories have made it clear that GaN and related wide-bandgap semiconductors are promising materials for the application to high power, high temperature microwave electronics as well as optoelectronics.

In addition, nitride-based materials exhibit a strong excellent piezoelectric effect with piezoelectric coefficients almost an order of magnitude larger than other traditional III-V semiconductors [35]. Recent research has demonstrated the presence of internal electric fields in GaN-based heterostructures caused by piezoelectric effects and/or the difference in spontaneous polarization between AlGaN and GaN even in the absence of strain [36-39].

Spontaneous polarization is not well defined, as has been discussed by King-Smith and Vanderbilt [40], and Resta [41]. Nitrides lack inversion symmetry and therefore exhibit piezoelectric effects when strained along the [0001] direction. Piezoelectric effects in GaN-based heterostructures consist of two components, i.e., due to thermal strain caused by the difference in thermal expansion coefficients, and due to lattice mismatch strain, as shown in Fig. 1.6. Polarization in wurtzite nitrides depends on whether the single bonds along the c-direction are from cation sites to anion sites or vice versa. When the single bonds along the c-direction are from cation sites (Ga) to anion sites (N), the polarity is denoted as Ga-polarity or Ga-face, and the
crystallographic direction is referred to as [0001]. For single bonds in the opposite direction, the polarity is denoted as N-polarity or N-face.

Fig. 1.6 (a) Relevant lattice constant differences for Al, Ga, In, N systems; and (b) bandgap and piezoelectric polarization versus lattice constants [26].

Polarization effects can increase or decrease interfacial free carrier concentrations in AlGAN/GaN and InGAN/GaN heterostructures [42]. For example, as shown in Fig. 1.7, coherently strained Al$_x$Ga$_{1-x}$N on a relaxed GaN substrate results in a piezoelectric polarization effect from the tensile strain with the same sign as the spontaneous polarization for Ga-face material. The sign of the polarization produces a potential gradient for electrons moving down from the AlGAN surface towards the AlGAN/GaN interface, and to drive electrons towards the two-dimensional electron gas (2DEG) that forms at this interface.
As discussed above, the wurtzite nitrides have exceptional spontaneous polarization and strong piezoelectricity, which make them promising candidates for applications in novel chemical, gas, biological and pressure sensing devices [27], surface acoustic wave devices (SAWs) [43], microelectromechanical (MEMS) systems, and applications under high temperature and harsh environments.

Another interesting property of GaN and many other group III nitrides is that they are distinguished by their unusual chemical stability. This is advantageous for achieving long device lifetimes, but makes fabrication processing more challenging. GaN is immune to etching in most common acids and basic etchants at room temperature. At present, the most successful etching techniques for GaN have been based on dry etching methods, including reactive ion etching (RIE) [44], electron cyclotron resonance (ECR) RIE [45], inductively coupled plasma (ICP) RIE [46],
chemically assisted ion beam etching (CAIBE) [47], low energy electron enhanced etching (LEEEE) [48], and reaction ion beam etching (RIBE), but the unavoidable ion-induced damage in these processes can compromise the performance of the final devices [49, 50]. In addition, these etch processes are often slow, precluding the fabrication of devices with large feature depths.

Although much work remains to be done in the areas of growth, materials study, fabrication processing, and device design to further enhance the performance of GaN-based devices, the development of a suitable micromachining technology has the potential to make significant technological impact on the fields of short-wavelength optoelectronics and high power microwave electronics. The ability to micromachine GaN and related materials offers the possibility of substantially improving the performance of existing devices, as well as making new types of devices. For example, for sensor applications, the ability to fabricate a suspended membrane is a critical but challenging process. Prior to the research presented here, the only demonstrated technique capable of forming a free-standing membrane was based on a rather complicated process using two-side photolithography and back side spray etching [51]. In this research, a simple and viable selective wet etching method capable of obtaining the desired etching profile, including formation of free-standing membranes, has been developed and demonstrated.
1.2 Review of current work

The foundation of micromachining in any material system is the ability to achieve the desired shape and edge profile of the feature being defined. For semiconductor-based processes, this is generally implemented by a range of etch processes in order to tailor the material removal rate and sidewall profile to the particular devices being fabricated. For GaN and related materials, much work has focused on using RIE-based dry etching methods including RIE, ICP, ECR and RIBE [44-48]. Shul et al. compared some variations of the RIE processes [52]; in summary, RIE yields the slowest GaN etch rates and generally results in sloped etch profiles, while ECR- and ICP-RIE can achieve considerably higher etching rates, and more anisotropic edge profiles. RIBE also can achieve anisotropic etch profiles, but with generally slower etch rates than ECR- or ICP-RIE. Due to the strong chemical bond energy in group III-N materials, either high ion energy or high ion flux at energies above the bond-breaking threshold is required. With all of these dry etching processes, plasma-induced damage is inevitable on the sample surface [53]. In contrast, the etched surface after wet chemical etching is negligibly damaged, and requires much simpler experimental apparatus compared with dry etching techniques. However, to date, room temperature wet etching of group III-nitride films has produced relatively slow etching rates. Elevating the temperature can increase the etch rates to some degree. For example, Sheng et al. reported an etch rate of approximately 0.5 nm/min for AlN in H₃PO₄ heated to 65 - 85 °C [54, 55]. However,
AlN is the most reactive of the III-Nitride compounds, and it has been noted that thermal treatment up to 85 °C in common acid and basic etchants is not effective for etching GaN [56]. In addition, the etching rates of GaN in oxalic acid (75 °C), phosphoric acid (82 °C) and sulfuric acid (82 °C) are almost zero [54, 55]. In order to circumvent this difficulty, more sophisticated processing methods are required.

One approach that appears promising is photoelectrochemical (PEC) etching [57, 58]. PEC etching is a modification of electrolytic etching, in which photogenerated electron-hole pairs take an active part in the etching process. Pankove [59] first demonstrated electrolytic etching of GaN in 1972, with the GaN acting as the anodic electrode of an electrochemical cell. In this early demonstration of electrolytic etching, the GaN sample was oxidized by applying a positive bias, resulting in a very low etch rate, although no particular etch rate was reported. To improve the etch process, optical illumination can be applied during electrolytic etching to form the PEC etching method. Minsky et al. successfully used the PEC method to etch GaN with KOH and HCl solutions under UV HeCd laser illumination [60]. Similarly, Skriniarova et al. demonstrated PEC etching of GaN in AZ400K photoresist developer, a KOH-based solution [61]. L. H. Peng et al. explored the pH dependence of the PEC etching rate for GaN in aqueous H₃PO₄ and KOH solutions [62]. C. Youtsey and coworkers successfully demonstrated many useful properties of PEC etching of GaN materials [63]. Selective etching of n-type GaN with respect to intrinsic and p-type GaN has been achieved [63], and the PEC method was demonstrated as a tool to reveal the dislocation microstructure of n-type GaN films.
by selectively removing material between dislocations \[64, 65\]. Youtsey et al. also showed that relatively smooth etching profiles occur under conditions of low KOH solution concentration and high light intensities \[66\]. J. S. Lee et al. first reported gate recess etching with the PEC technique for the fabrication of an AlGaN/GaN heterostructure field effect transistor \[67\], and it is further investigated by Su et. al. \[68\]. Recently, H. M. Ng et al. demonstrated the fabrication of GaN nanotip pyramids by selective and anisotropic etching of N-polarity GaN in KOH solutions \[69\], and patterned GaN microstructures by polarity-selective chemical etching \[70\]. Y. Gao et al. investigated the dislocation- and crystallographic-dependent photoelectrochemical wet etching of GaN \[71\]. D. J. Diaz et al. did research work on morphology evolution and luminescence properties of porous GaN generated via Pt-assisted electroless etching of hydride vapor phase epitaxy grown GaN on sapphire \[72\].

Although PEC etching has been studied by a number of researchers \[57-68, 71-77\], further effort was still warranted, as many fundamental questions remain. For example, the physical mechanism responsible for PEC etching of GaN is not yet fully understood. In addition, etch process control has not yet progressed to the point that a given shape and sidewall profile can be readily achieved. To accurately control the etching and achieve clear undercut structures and suspended membranes needed for many MEMS and sensor applications is also still a significant challenge. On a more fundamental level, the understanding of the materials properties and the relationship between Al mole fraction in AlGaN and the variation of fundamental material properties such as permittivity is also very limited. The research described here has
been directed at answering these and other fundamental questions in PEC etching of GaN and related materials.

1.3 Description of the research

In summary, there are two main parts in this research dissertation. First, a viable micromachining technology for GaN has been developed, which has the potential for wide-ranging impact on the fields of high power and high temperature microwave electronics as well as short-wavelength optoelectronics. The mechanisms that govern PEC etching have been studied in detail. This study is complicated by the fact that etching results depend on many factors, including material properties such as chemical composition, doping concentration and density of defects, as well as on the etchant, applied voltage and light intensity. To establish an etching model, the relationship between etch rate and solution concentration, illumination intensity of UV light, sample-solution bias voltage, and the etching current have been investigated and a model has been proposed. The control of etched surface morphology is demonstrated, and etch conditions suitable for forming undercut structures and suspended membranes by PEC etching have been identified and demonstrated.

Secondly, as an example of a novel device enabled by the micromachining technology developed, an inline transmissive microwave power sensor has been designed and simulated. This power sensor is designed to be easily integrated with
high power GaN-based HEMTs, providing the ability to directly measure output power over wide bandwidth without the need for large electromagnetic coupling structures. The simulations show that power detection can be accomplished with minimum impact on the system, and only a small loss of the microwave power.

The remainder of this thesis is organized as follows: Chapter 2 investigates PEC etching of GaN, and discusses the model developed for the PEC etching process; Chapter 3 investigates and discusses the etched surface morphology control during PEC etching, in which solution concentration, illumination intensity and voltage effects are all exploited. Chapters 4 and 5 investigate and demonstrate the formation of undercut and suspended membrane etch profiles using PEC etching. Chapter 6 describes the design and simulation of a novel power sensor enabled by the developed micromachining processes. Finally, the research conclusions are summarized in Chapter 7, and suggestions for future research are also given.
CHAPTER II
PHOTOELECTROCHEMICAL ETCHING OF GALLIUM NITRIDE

2.1 Introduction

Electrochemistry is the foundation for understanding the mechanisms of etching, deposition and corrosion, and plays an important role in the development of integrated circuit (IC) technology. Photoelectrochemical (PEC) etching, as one interesting area in this field, is a technique encompassing light-induced generation of electrons and holes assisting electrochemical reactions of semiconductors in contact with an electrolyte. When immersed in an electrolyte, the semiconductor exchanges electrons with the electrolyte along the surface because the Fermi level in the semiconductor is different from that of the electrolyte. Like semiconductor-metal contacts, an energy barrier is formed, the effective height of which is often fixed by the distribution of surface states in the semiconductor. At the same time, a source of light whose photon energy is greater than the bandgap energy of the semiconductor illuminates the semiconductor surface, resulting in pairs of electrons and holes being photogenerated. The electrons and holes created in the space-charge region near the surface are transported by two mechanisms, drift under the influence of the electric field, and diffusion due to the carrier concentration gradient.
Figure 2.1 shows energy band diagrams for n-type and p-type semiconductors in contact with an electrolyte. For this illustration, it has been assumed that the semiconductor Fermi level is pinned within the bandgap at the surface. For the n-type semiconductor, photogenerated holes accumulate at the surface. This hole-accumulation is fundamental to PEC etching. Since the presence of a hole at the surface is essentially a broken chemical bond, the holes allow oxidation and dissolution of the semiconductor by the electrolyte. The chemical reaction for this oxidation-dissolution process is the sum of many sequential one-electron transfer steps and chemical reactions [58]. For p-type materials, holes are depleted from the
interface, and thus cannot contribute to oxidation of the semiconductor. This leads to the doping-induced selective etching effect reported by Youtsey et. al. [63], and Strittmatter et al. [78]. One possible approach to circumvent this obstacle is to apply a bias voltage between the semiconductor and the electrolyte. The applied bias bends the energy bands, thus enabling holes to accumulate at the surface.

There are many useful properties of PEC etching. Some interesting and important attributes are summarized below:

1. Light intensity dependence and spatial selectivity. The rate of etching depends on the rate of photogeneration of electron-hole pairs. Surface relief etching can be implemented by spatial modulation of the incident light [58, 79, 80].

2. Bandgap selectivity. In a multilayer structure consisting of layers with different bandgaps, the narrow gap layers can be selectively etched, depending on the wavelength of the incident light used [58, 81]. The wide bandgap materials are almost transparent to photons whose energy is less than the material bandgap. We have explored the use of this property to fabricate free-standing membranes.

3. Dopant-type selectivity. As shown by Youtsey et al., n-type GaN can be selectively etched with respect to p-type GaN because of the existence or depletion of holes at the GaN/electrolyte surface [63, 78].

4. Anisotropic etching. Because of the short carrier lifetime and limited diffusion length of photogenerated holes in GaN, on the order of 100 nm [82,
83], etching proceeds only near the regions illuminated with UV light. Using optically opaque mask materials (e.g. Ti films) to block light, etching under the mask is prevented from taking place as a result of no holes being photogenerated in the masked regions.

5. Real time monitoring of the etch process. The etch rate and amount of material dissolved can be monitored by measuring the current flowing in the sample-electrolyte loop. This requires a detailed understanding of the electrochemical mechanism of PEC etching of the studied materials, but enables the progress of the etch process to be monitored in real time.

2.2 Experimental setup

Two different GaN–based epitaxial structures have been used for the study of PEC etching of GaN. Table 2.1 summarizes these structures. All material was grown by metalorganic chemical vapor deposition (MOCVD), with a c-plane crystal orientation on sapphire substrates.

**TABLE 2.1 LIST OF MATERIALS IN STUDY**

<table>
<thead>
<tr>
<th>Sample</th>
<th>Epitaxial Structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample type 1, supplied by Advanced Technology Materials, Inc.</td>
<td>1.5 µm GaN (n-type, (N_e=7\times10^{16} \text{ cm}^{-3})) / 1.5 µm undoped GaN buffer / Sapphire</td>
</tr>
<tr>
<td>Sample type 2, supplied by Technologies &amp; Devices International, Inc.</td>
<td>~5.5 µm GaN (undoped)/ Sapphire</td>
</tr>
</tbody>
</table>
For etching studies, a metal etch mask was used and consisted of 150 nm to 200 nm thick Ti that was deposited on the sample surface by electron-beam evaporation and patterned by lift-off. Figure 2.2 shows a schematic drawing of the apparatus used for the PEC etching study. The GaN samples were mounted on a Teflon holder in an electrochemical cell. An insulated tungsten probe tip is used to contact the metal on the sample. A platinum wire was inserted in the KOH solution to act as the system cathode. No bias was applied between the sample and the platinum wire except as noted. Depending on the required light intensity, either a 200 W or a 1000 W mercury (xenon) short arc lamp from Oriel Inc. was used as the UV light source. The light spectra provided by the light sources are shown in Appendix A. The light source also contains a built-in shutter in the lamp housing to switch the incident
UV light on or off. The light intensity can be adjusted by changing the focal length of the collimating lens through which the UV light passes. In addition, the incident direction of the UV light can be from the top side (as shown in the schematic) or from the back side through the bottom of the cell. A Keithley Model 2400 Sourcemeter™ was used to measure the current in the loop formed by the sample, electrolyte, and Pt cathode. A computer was connected to the current meter through a GPIB interface with a basic communication C program (shown in Appendix B), and monitored the current flowing in the loop in real time. After etching, etch depths were measured using an Alpha Step 500 profilometer, and etch morphologies were examined with a Hitachi S-4500 FESEM.

2.3 Results and Discussion

2.3.1 Ti-GaN contact

Transfer Length Method (TLM) theory originally proposed by Shockley [84] was used to determine the quality of Ti-GaN contacts in this study. A schematic drawing of a semiconductor with metal contacts for TLM analysis is shown in Figure 2.3. A current is passed between two adjacent metal pads through two probes, while a second set of probes are then used to measure the voltage drop. Then, the total resistance between the pads can be obtained using:

\[ R_{\text{tot}} = \frac{V}{I} \]
From Figure 2.3, the total resistance, \( R_{\text{tot}} \), between two adjacent pads, is given by:

\[
R_{\text{tot}} = 2R_{\text{pad}} + R_{\text{semi}}
\]

where \( R_{\text{pad}} \) is the resistance due to the metal-semiconductor interface at each pad, and \( R_{\text{semi}} \) is the resistance due to the semiconductor material.

![Schematic drawing of metal pad preparation for TLM analysis.](image)

The TLM measurement process is repeated for varying pad-to-pad spacing, and the total resistance is plotted on a linear graph as a function of pad spacing. On a graph of this form, the y intercept at space = 0 is \( R_{\text{tot}} = 2R_{\text{pad}} \), giving the contact resistance. A typical measurement result is shown in Fig 2.4. The size of one metal pad is about 100 x 68 \( \mu \text{m}^2 \), and the intercept is 552.48 ohms. The product of metal pad size and the intercept leads to a specific contact resistance of about \( 1.9 \times 10^{-2} \) ohm-cm\(^2\). Although it has been shown that the contact resistance can be improved by annealing at high temperature, such alloy anneals also introduce contamination (due to metallic diffusion) under the Ti metal masks [85]. Thus, annealing steps were not used for GaN samples in the following experiments.
Fig. 2.4 TLM measurement of typical Ti/GaN contact test structure.

Fig. 2.5 Schottky barrier height at the metal/GaN interface measured by different techniques versus metal work function [86-90].
Figure 2.5 summarizes published literature data on the Schottky barrier height for various metal contacts to GaN and AlGaN as measured by different techniques versus metal work function [86-90]. From the data, Ti metal is the best selection for forming contacts for PEC etching due to its low barrier height as well as its immunity to attack by the primary PEC electrolyte, KOH.

2.3.2 GaN-Electrolyte contact

When a GaN sample is immersed into the electrolyte, the GaN electrode-electrolyte interface energy band diagram resembles a semiconductor-metal interface. Huygens et al. [57] investigated the electrochemistry of n-GaN in KOH solutions, and summarized the relationship between the flatband potential $V_{FB}$ and the pH by the following relation:

\[
V_{FB} = -0.78 - 0.060pH \quad \text{(in V vs. SCE)}
\]

where SCE stands for saturated calomel electrode as the reference potential.

From our experiments, the most useful concentrations of KOH electrolyte solutions are from 0.001 M to 0.05 M, corresponding to a pH value in the range of 10 to 13. This corresponds to flatband potentials from 1.38 to 1.56 V. The interface
potential barrier is the sum of the flatband potential and the separation between the conduction band and Fermi level in the semiconductor bulk.

Figure 2.6 shows energy band diagrams for n-type GaN in contact with an electrolyte under several different conditions. When no UV light is used to illuminate the semiconductor, the Fermi levels on both sides should be equal when equilibrium is reached between sample and solution, as shown in Fig. 2.6(a). When the UV light is on, and the circuit is open – and thus no current can flow - the energy band diagram changes to that shown in Fig. 2.6(b). The typical band diagram for PEC etching is as shown in Fig. 2.6(c), where instead the GaN sample and electrolyte are shorted by a wire between the GaN contact and the Pt cathode. When UV light illuminates n-type GaN, the photogenerated electrons are pushed into the bulk of the semiconductor by the surface electric field. On the other hand, photogenerated holes move toward and accumulate at the surface. This hole accumulation is fundamental to PEC etching, since the presence of a hole at the surface works essentially as a broken chemical bond. As a result, the holes facilitate oxidation and dissolution of the semiconductor by the electrolyte. In general, the chemical reaction for this oxidation-dissolution process is the sum of many sequential one-electron transfer steps and chemical reactions.
Fig. 2.6 Energy band diagram of n-type GaN in contact with an electrolyte under different conditions: (a) equilibrium; (b) illumination and open circuit; and (c) illumination and short circuit. The latter is the typical setup for PEC etching.
2.3.3 Diffusion-limited PEC etching vs. reaction rate limited PEC etching

With a type 1 sample (n-GaN, see Table 2.1), a layer of Ti 200 nm thick was deposited on the top surface, serving as an opaque mask for PEC etching after patterning. The sample was immersed in 0.02 M KOH solution, and the intensity of the incident UV light was set to 20 mW/cm². The built-in shutter was used to control the duration of the UV light illumination and then the etching current was recorded with the computer through the GPIB interface. A typical current vs. time characteristic is shown in Figure 2.7.

Fig. 2.7 Typical time dependence of PEC etching current for GaN in KOH solution.
It was found that the current under illumination depends on whether the probe tip is in direct contact with the Ti mask or in direct contact with the GaN surface. The current was found to be about 5% higher when the tip contacts the Ti masking material. The following results are all under conditions of direct contact between the probe and the Ti mask. It was also observed that even when the shutter is closed, the measured current is not exactly zero. In order to rule out the possibility of electrolytic etching of GaN without illumination, a sample was put in the same KOH solution for 3 hours without illumination. We found using SEM that the GaN was not etched perceptibly. Consequently, it appears that the dark current arises from parasitic reactions between the probe tip, Ti mask and KOH solution, and does not contribute in any significant way to the etching of GaN.

Figure 2.8 shows two different SEM micrographs after PEC etching. Two GaN samples made from type 1 material were etched in the same concentration solution of 0.02 M KOH using the same light intensity of 20 mW/cm², with and without agitation. As can be seen in the figure, whether the solution is agitated or not makes a great difference in determining the resulting etching morphology. The etched surface is much smoother without stirring compared with the surface obtained with stirring of the solution.
Fig. 2.8 Scanning electron micrographs showing GaN morphologies after etching in 0.02 M KOH for 15 minutes under different conditions: (a) without agitation, (b) with agitation by stirring.
A schematic diagram of the interface between the electrolytic solution and GaN sample is shown in Figure 2.9. As indicated in the figure, the concentration of KOH in the electrolyte solution decreases near the interface as a result of consumption of KOH through reaction between the solution and the sample. This results in the creation of a depletion region in the solution as shown in Figure 2.9. The KOH consumed at the semiconductor surface is replenished by diffusion of KOH from the bulk of the solution. Balance between consumption at the surface and the diffusion from the bulk produces a dynamic equilibrium concentration gradient. Under these conditions, the PEC etching rate is controlled by the diffusion speed, and any protrusions from the sample’s surface experience a somewhat higher KOH concentration – and thus dissolution rate. As a result, in a comparatively smooth...
surface morphology as shown in Figure 2.8(a) is obtained. With stirring of the solution, however, the concentration gradient within the solution is disturbed and no depletion region can be established. The agitation maintains the concentration at almost the same level throughout the solution. Under these conditions, the PEC etching primarily depends on the reaction rate between the sample and the solution, and the etching result is shown in Figure 2.8(b). Although additional investigation of the observed phenomena is needed (and will be discussed in the following sections), it is evident that non-stirred PEC etching produces a much smoother surface. Consequently, the following experiments are all carried out without stirring of the solution, except as noted.

![SEM image of the observed “trench” near large masked area.](image)

Fig. 2.10 SEM image of the observed “trench” near large masked area.
It is noted here that “trench” formation is also observed near large masked areas. Figure 2.10 shows a 600 x 100 μm$^2$ masked feature for which the Ti metal has been removed (using 10:1 buffed HF) after PEC etching in 0.02 M KOH. As can be seen, a trench is formed around the periphery of the masked area. The effect is consistent with a diffusion-rate-limited etch process, and occurs because the local electrolyte concentration at the edge of masked features is higher than in areas far away from the mask, since no consumption of KOH takes place in masked areas. As a consequence, the etch rate is enhanced at the periphery of large masked features, and trenches such as that shown in Fig. 2.10 can form.

2.3.4 Mechanism of PEC etching of GaN

A study of PEC etching as a function of KOH solution concentration and illumination intensity was performed. Figure 2.11 shows that during PEC etching, the etching current increases with increasing light intensity or increasing KOH solution concentration. The same sample was used repeatedly in this study in order to ensure that the etching area was constant throughout the study. The currents shown in Figure 2.11 reflect the values obtained after the current stabilizes following the transient that occurs when the shutter is first opened. In addition, the reported current is the difference between the shutter-open value and the measured dark current. For high concentration solutions, the dark current is found to be higher than for lower concentration solutions.
It has been accepted by many researchers that the following reaction equation is responsible for the PEC etching of GaN [91-93].

$$2\text{GaN} + 6h^+ \rightarrow 2\text{Ga}^{3+} + \text{N}_2 \quad \text{(Eq. 2.1)}$$

According to Faraday’s law of electrolysis, the number of moles of substance produced or consumed at an electrode during electrolysis is directly proportional to the number of moles of electrons transferred at that electrode. Thus, the mass of GaN removed from the sample being etched is directly related to the PEC etching current.
From Equation 2.1, it is easy to explain the increase in etching current with high light intensity, because more holes are generated by more photons. However, it should be pointed out that this mechanism cannot explain the observed change of the time dependence of the PEC etching current with respect to different concentration solutions shown below in Figure 2.12.

From Figure 2.12, the etching currents for lower concentrations of KOH show a decreasing trend during the etch process. The trend of the 0.001 M etching current curve is clearly different from that of the 0.06 M solution, whose etching current is rather stable for the duration of the PEC etch. The etching current is related to the size of the etched sample area and the number of photogenerated holes, according to equation 2.1. Neither of these factors varies during the PEC etching under conditions of constant light intensity. It is also well known that the etching current is proportional to the etching rate according to Faraday’s law of electrolysis. Thus, an underlying mechanism that retards the etching of GaN in KOH solutions of lower concentration is at work.

A possible explanation for this effect is the presence of a residual oxide film formed on the GaN surface during PEC etching. This residual oxide can act as a spacer which separates the GaN surface from the KOH solution, thus retarding etching. With a high KOH concentration solution, the oxide formed during etching can be dissolved more efficiently and quickly, so the retarding effect is minimal.
Fig. 2.12 Time dependence of etching current in different concentrations of KOH solution: (a) 0.001 M, (b) 0.002 M, (c) 0.005 M, (d) 0.06 M. The illumination light intensity is 70–80 mW/cm$^2$. 
To verify the formation of oxide during PEC etching, X-ray photoelectron spectroscopy (XPS) was performed on PEC-etched surfaces, and compared to the results from as-grown GaN. As shown in Figure 2.13, the GaN sample surface after PEC etching exhibits an appreciably increased oxygen peak compared to an as-grown GaN sample, indicating the formation of oxide. When the PEC-etched sample was cleaned by immersing it into 0.5 M KOH solution for 30 min, the oxygen peak area decreased, indicating the dissolution of the oxide in KOH.

![X-ray photoelectron spectroscopy (XPS) of O 1s.](image)

Thus, the PEC etching model can be revised to a two-step model. At first, an oxide layer is formed, governed by equation 2.2:

\[
2\text{GaN} + 6 \text{OH}^- + 6h^+ \rightarrow \text{Ga}_2\text{O}_3 + 3\text{H}_2\text{O} + \text{N}_2 \quad \text{(Eq. 2.2)}
\]
Then, the oxide is dissolved in the KOH solution for the second step:

\[
\text{Ga}_2\text{O}_3 + 6\text{OH}^- \rightarrow 2\text{GaO}_3^{3-} + 3\text{H}_2\text{O} \quad \text{(Eq. 2.3)}
\]

Both holes and OH\(^-\) ions take active parts in the etching of the GaN. It should be noted that the two-step process described by equations 2.2 and 2.3 is essentially equivalent to the overall reaction described by equation 2.1. It has been observed that bubbles are often found near the surface of the sample during PEC etching, which may be the release of N\(_2\).

The decreasing trend of etching current with respect to time may come from either the formation of a solution depletion region or the formation of a surface oxide that retards etching, or a combination of these effects. For the former case, as the PEC etching proceeds, the concentration of OH\(^-\) at the sample surface decreases because OH\(^-\) is consumed by the etching process of GaN. When the density of OH\(^-\) is lower, the etching rate should decrease, according to the rate of reaction relation in Equation 2.4:

\[
\text{Reaction rate} = K [A]^m [B]^n \quad \text{(Eq. 2.4)}
\]

In this expression, K is the rate constant for the reaction, [A] is the concentration of A, [B] the concentration of B, m is the order of the reaction with respect to A, and n is the order of the reaction with respect to B. The reaction order depends on the mechanism of the reaction and not on the stoichiometry. Because of
the complexity of the PEC etching reactions, it is often treated as a pseudo-first-order reaction [58, 94]. To a first approximation, the reaction rate depends on the frequency of collision between the reactants, which will increase for elevated temperature, increased reactant concentration, or agitation of the active electrolyte.

Applying this relationship to the reaction described by Equation 2.2,

\[
\text{Reaction rate of Eq. 2.2} = K \ [\text{OH}^-]^m \ [\text{h}^+]^n \quad \text{(Eq. 2.5)}
\]

Similarly, for reaction 2.3,

\[
\text{Reaction rate of Eq. 2.3} = K \ [\text{OH}^-]^n \quad \text{(Eq. 2.6)}
\]

From Equation 2.6, the Ga$_2$O$_3$ formed cannot be dissolved effectively in lower concentration KOH solutions due to limited availability of OH$^-$ ions. The residual Ga$_2$O$_3$ layer impedes the PEC etching further by limiting the availability of un-reacted GaN at the surface. Thus, the electrolyte depletion region naturally gives rise to an un-dissolved surface oxide film, and so these two effects – solution depletion and surface oxide formation – are intimately coupled. For oxidation, the OH$^-$ ions have to diffuse through this additional oxide layer to react with the sample. Since the etch is retarded by an oxide layer, the etching current decreases according to Faraday’s law of electrolysis which states that the etching current is directly proportional to the rate of mass removed by etching. As shown in Figure 2.12(a), the etching current drops down until a dynamic equilibrium state is reached in which the
dissolution of the oxide is the same as to the PEC oxidation of the GaN. The decrease of the PEC etch current is thus caused by this combination of solution depletion and the accumulation of surface oxide before reaching dynamic equilibrium. On the other hand, for a high concentration solution such as shown in Figure 2.12(d), the layer of gallium oxide is more easily dissolved according to Equations 2.3 and 2.6. As a result, the etching current is stable as shown in Figure 2.12(d).

![Graph showing time dependence of etching current with different shutter-closed times](image)

Fig. 2.14 Time dependence of etching current with different shutter-closed time: 90 s, 30 s, and 2 hours. The concentrations of KOH solution is 0.001 M. The illumination light intensity is 70~80 mW/cm².

The formation of oxide on the etched surface also explains the observed time dependence of etching current with different shutter-closed times, as shown in Fig. 2.14. After putting the sample in the electrochemical cell, the etching current progressively falls in low concentration KOH solution (0.001 M). The light source used in this experiment has a built-in shutter which switches the incident light on or off. The shutter was closed after an apparent steady-state was achieved, and then
reopened after different dark times: 30 s, 90 s and 2 hours. This process is illustrated in Fig. 2.14.

When the light is off, only the dissolution of the oxide occurs. Dramatically different peak current values were observed when the light was switched on again, depending on the duration of the dark period. With a longer shutter-closed time, the peak current value is much closer to the initial current peak. This suggests that the residual oxide is more fully dissolved after a longer dark time, and thus has less of a retarding effect upon re-opening the shutter. Note too that the long dark times required preclude the possibility that this effect - the slowed etching - is due solely to an electrolyte depletion effect, since room-temperature solution concentration gradients cannot be maintained on such a long time scale. However, it is observed if the PEC etching current increases immediately when the solution is agitated during initially non-stirred PEC etching, but the PEC etching peak current after agitation is not as high as the initial etch current transient peak. Consequently, it can be concluded that both the formation of a concentration depletion region in the solution and the formation of a residual oxide layer in lower concentration solutions influences the behavior of the time dependence of PEC etching current. It is difficult to unambiguously determine the individual effect caused by either concentration depletion region or residual oxide, since they are intimately coupled as discussed previously. Consequently, although the observation that the trend of time dependence of etch current in lower concentration as shown in Fig. 2.12(a) has an approximately
parabolic form, consistent with expectation for the growth of a residual oxide layer, the effect of the concentration depletion can not be fully excluded.

In order to investigate the formation and properties of the residual oxide, the GaN sample (~14 µm GaN grown on sapphire substrates with unintentional n-type doping density $6 \times 10^{16}$ cm$^{-3}$) was inserted into the PEC cell with 0.001 M KOH for 5 hours, and an illumination intensity of 350 mW/cm$^2$ was used. To facilitate the use of variable-angle spectroscopic ellipsometry (VASE) to investigate the properties of the residual oxide layer, a sample big enough to fully encompass the light spot produced by VASE is needed. The size of the sample used was approximately 1.2 x 1.2 cm$^2$, and the Ti metal contact to the sample only covers one corner in order to avoid the possible interference with the VASE measurement. Optical microscope images of the samples before and after PEC etching are shown in Figure 2.15. From the images, it is clear that the surface color changes after the PEC etching, indicating the formation of the oxide layer. The cross-sectional side view and top view were also examined by SEM, as shown in Figure 2.16. From Figure 2.16 (a), three layers are evident: sapphire substrate, GaN, and residual oxide layer. The thickness of the oxide layer is up to 2 µm. After tilting the sample for SEM examination to get a top view, it is noted that the oxide layer has many cracks and defects, as shown in Figure 2.16 (b). This sample was measured using the VASE, but because of the rough, cracked and non-uniform oxide surface and the rough oxide-GaN interface, the intensity of the light reflected from the sample is very low, and accurate determination of film properties could not be obtained. Samples were also prepared and treated using higher PEC
electrolyte concentrations. As the solution concentration increases, it is found that the thickness of the residual oxide decreases dramatically. As shown in Fig. 2.17, the thickness of the oxide layer is much less for GaN samples PEC-etched in 0.002 M KOH electrolyte than in 0.001 M KOH solution, i.e., 190 nm for 0.002 M KOH versus 2 µm for 0.001 M. Again, however, the non-uniformity prevented an accurate VASE measurement.

Fig. 2.15 Microscope images of GaN sample surfaces, (a) before PEC etching, and (b) after PEC etching in 0.001 M KOH electrolyte for 5 hr. The light intensity is 350 mW/cm².
Fig. 2.16 SEM images of GaN sample after PEC etching in 0.001 M KOH electrolyte for 5 hr, (a) cutaway side view, and (b) tilted top view. The light intensity is 350 mW/cm$^2$.

Fig. 2.17 SEM images of GaN sample after PEC etching in 0.002 M KOH electrolyte for 5 hr, (a) cutaway side view showing an oxide layer thickness of 190 nm, and (b) tilted top view. The light intensity is 350 mW/cm$^2$. 
2.3.5 PEC-etched GaN surface morphology study

Figure 2.12 and Figure 2.18 show the time dependence of etching current and SEM micrographs respectively for four concentrations of solution, 0.001 M, 0.002 M, 0.005 M and 0.06 M. The samples were made from materials of type 2 (see Table 2.1), using a Ti metal mask.

As can be seen in Figure 2.18, a grass-like etching morphology is obtained with high concentrations. It has been previously reported that holes are depleted at threading dislocations in GaN due to a high non-radiative recombination velocity [95]. For our GaN samples, the density of dislocations reaches as high as $10^{12} \text{ cm}^{-2}$ according to information from the crystal vendor. So, the distribution of the photogenerated holes may take the form shown schematically in Figure 2.19(a).

Combining Equation 2.1 with the distribution of holes on the surface shown in Fig. 2.19, it is possible to explain the cause of the formation of the grass-like etching morphology. From Equation 2.1, we can see that the etch rate mainly depends on the density of holes at the semiconductor surface. The non-uniform density of holes at the surface arises from the combination of a spatially uniform electron-hole pair generation rate and rapid hole recombination in the vicinity of dislocations. The density of holes is higher in the undefected GaN region than near dislocations. Consequently, the crystalline GaN regions are preferentially etched. The areas near dislocations are etched at a lower rate, and grass-like structure is formed. It has been verified by TEM analysis that a close correlation exists between grass on the etched
surface and the dislocation density of the material. In previous TEM studies, whiskers were observed to originate directly at dislocations [64].

Fig. 2.18 SEM micrographs of PEC-etched GaN samples in different concentrations of KOH solutions: (a) 0.001 M, (b) 0.002 M, (c) 0.005 M, and (d) 0.06 M. For each case the light intensity was 70-80 mW/cm², and the samples were etched for 98 minutes.
Fig. 2.19 (a) Schematic illustration of distribution of photogenerated holes with respect to dislocations on sample surface; (b) SEM magnification of grass-like surface morphology after PEC etching in 0.002 M KOH.
As the intensity of UV illumination is increased, the density of holes should increase both in perfect crystalline GaN and near the dislocations. Since recombination at defects is characterized by a reduced, but finite, carrier lifetime, the depressed etching rate near defects becomes less pronounced as illumination intensity is increased. Thus, the difference in etch rates between material near dislocations and crystalline material is reduced. Although qualitatively plausible, this explanation for the observed surface morphology remains to be conclusively proved. As an oxide, one interesting application of PEC etching is to evaluate the material quality of GaN, utilizing this difference of etch rates between crystalline and dislocated materials to provides a way of measuring defect densities.

To investigate the role a surface oxide film plays in the formation of this grass-like morphology, the same samples after PEC etching as shown in Fig. 2.18 were subsequently immersed in stirred boiling 0.5 M KOH solution, since it is expected that gallium oxide should be dissolved in stirred high concentration KOH solutions at elevated temperature. Figure 2.20 (a), (b), (c) and (d) are the resulting SEM micrograph images. As can be seen, the SEM micrographs of the samples treated with an additional KOH solution at elevated temperature are quite different from the original ones. The preceding PEC-etching-generated surface oxide and the grass-like morphology have been removed. The final etching surfaces in 0.001 M, 0.002 M KOH solutions are rather smoother than that in 0.005 M solutions. This may be due to the mediating effects of the thick residual surface oxide layer. For micromachining applications, a high etch rate is desirable to permit rapid fabrication
of micro-scale features. However, as shown in Figure 2.20 and Figure 2.21, the etch rate decreases with decreasing concentration, though small concentrations are needed for smooth morphology. There is thus a trade-off between achieving a smooth surface and obtaining a reasonable etch rate. To circumvent this trade-off, a possible method is to use PEC etching in a rather high concentration solution for a high etch rate at first, then follow this process by high temperature KOH chemical etching to get a smooth and clear surface, as discussed previously.

For comparison, a GaN sample without PEC etching at first was also immersed in 0.5 M KOH solution at a temperature of 150 °C for 30 minutes. In this case, no etching of GaN was perceptible, and the surface morphology did not change, as observed by SEM. Thus, the high temperature KOH treatment only affects the oxidized surface formed during PEC etching.

An interesting feature in Fig. 2.20(d) is the hexagonal etched holes observed. These originate from PEC etching into the GaN buffer layer with lower material quality, and the occurrence of crystalline-dependent etching [97, 98]. With still higher concentration solutions for PEC etching, GaN can even be PEC-etched into a porous formation, as shown in Fig. 2.22. This formation has also been observed by other researchers [72]. Clearly, a suitable concentration range is critical for good etched surface morphology.
Fig. 2.20 SEM micrographs of GaN samples which are first PEC etched in different concentrations of KOH solutions: (a) 0.001 M, (b) 0.002 M, (c) 0.005 M and (d) 0.06 M at the light intensity of 70-80W/cm² for 98 minutes, followed by immersion in 0.5 M stirred KOH solution at 150 °C for 30 minutes.
Fig. 2.21 PEC etching rate with respect to concentration of solution. The light intensity is 70-80 mW/cm².

Fig. 2.22 The formation of porous GaN; SEM micrographs of a GaN sample after PEC etching in 0.5 M KOH solution with light intensity of 70-80 W/cm² for 20 minutes.
2.3.6 Anisotropic property of PEC etching

One excellent property of photoelectrochemical etching of GaN is the extremely localized nature of the etch – PEC etching only takes place where the GaN region is illuminated and electron-hole pairs are photogenerated. From the above experiments and SEM images, anisotropic etching results are clearly shown. The Ti metal mask blocks the incident light and no etching takes place beneath the mask. We further investigated this property by designing a tilted PEC etching experimental setup, as shown in Fig. 2.23. The sample is clipped on a holder with 45° slope. The purpose is to investigate the formation of sloped etched profiles which are important in many optoelectronic devices [99, 100].

Fig. 2.23 Schematic drawing of tilted PEC etching setup.
Figure 2.24 is the SEM image of the etched result with a GaN sample made from type 2 material, following the same procedure as before in 0.005 M KOH for 2 hours. The Ti metal has been removed with buffered HF (10:1) after PEC etching, followed by immersion in 0.5 M stirred boiling KOH solution for 30 minutes. It is clear in Fig. 2.24 that a sloped etch structure forms. The reason for the sloped structure formation is that the mask defines the regions to be illuminated, as indicated in the Fig. 2.23.

![Fig. 2.24 SEM micrograph of tilted PEC etching of GaN.](image)
2.4 Conclusions

The mechanisms of GaN PEC-etching have been studied, and a two-step model that is consistent with experimental observations is proposed. The presence of gallium oxide, formed during PEC etching, has been verified with XPS. The formation of a grass-like etched surface morphology has been investigated, and several approaches for obtaining smooth surfaces have been demonstrated. The anisotropic etching properties of the PEC technique have been used to achieve sloped etched profiles.
CHAPTER III
SURFACE MORPHOLOGY CONTROL DURING PHOTOELECTROCHEMICAL ETCHING OF GALLIUM NITRIDE

3.1 Introduction

As discussed in previous sections, the potential of GaN and related wide bandgap nitride-based materials such as AlGaN and InGaN has been well demonstrated for applications in high power and high temperature high electron mobility transistors, blue, violet and ultraviolet LEDs, laser diodes [1-18]; and the photoelectrochemical (PEC) wet etching technique is an attractive approach since it overcomes the chemical inertness of GaN and offers the possibility of implementing wet etches for GaN. However, although photoelectrochemical etching shows promise as a method for low-damage processing, the PEC etch processes reported to date often result in rough etched surfaces [60-62, 64, 65]. For many electronic and optoelectronic devices, a smooth etched surface morphology is preferable.

As shown in Chapter 2, a stirred boiling KOH solution post-treatment after PEC etching can be used to improve the surface to some extent. Additionally, it has been found the grass-like structures are generally not fully removed if stirring is not used during the KOH post-treatment. Although stirring is often acceptable, for the formation of many fragile structures, it is desirable to avoid agitation. Even with stirring, however, the surface is not as smooth as might be desired. As an alternative
to hot KOH post-processing, by modifying the basic PEC etching configuration to include the addition of an external DC bias voltage to the PEC electrochemical cell, we have achieved simultaneously high etch rates and smooth etched surfaces. Smooth etched surfaces with surface roughness of 0.5 nm rms have been obtained, which is comparable to the original as-grown surfaces. In addition, the etch rate was dramatically enhanced, rising from 10 nm/min without applied bias to 18 nm/min for an applied voltage of +0.65 V, and 32 nm/min for +2 V. In this chapter, we report the dependence of the etch rate and surface morphology on the PEC process parameters, including electrolyte solution concentration, semiconductor doping, and bias voltage.

3.2 Experimental

In addition to the GaN materials used in chapter 2, GaN grown on sapphire substrates by metalorganic chemical vapor deposition (MOCVD) with doping concentrations of $6 \times 10^{16}$ cm$^{-3}$ (unintentionally n-doped) and $1 \times 10^{18}$ cm$^{-3}$ (Si doped) were used. The PEC etch apparatus was the same as described previously in Chapter 2. To obtain enhanced control of the PEC etching, however, a Keithley model 2400 source-monitor unit was used not only to measure the current flowing in the electrochemical cell loop consisting of the GaN sample, electrolyte, and Pt cathode, but also to apply a bias voltage between the sample and the Pt cathode. A 1000 W mercury (xenon) short arc lamp was used as the UV light source. A schematic drawing of the modified setup is shown in Fig. 3.1.
Fig. 3.1 Schematic of PEC etching experimental configuration with voltage bias applied.
3.3 Results and Discussion

3.3.1 Illumination intensity and solution concentration dependence

As seen in Chapter 2, a grass-like structure is often formed on the sample surface after PEC etching. For a deeper understanding of the formation of the grass-like surface structure, an investigation of the temporal evolution of grass formation with regard to time was undertaken. SEM images for GaN samples (material type 2, see Table 2.1) PEC-etched in 0.05 M KOH with different etching times are shown in Fig. 3.2.

As shown in Fig. 3.2(a), the surface morphology does not change after 1 minute etching; (b) after 3 minutes of etching, the surface has roughened noticeably; (c) a hill-like surface morphology forms after 5 minutes; and (d) by 24 minutes of etching, a grass-like morphology is obtained. As discussed in Chapter 2, selective PEC etching takes place between the undefected regions and the dislocation regions, leading to the rough grass-like surface.

In summary, from Fig. 3.2, it can be seen that the surface evolves into a rough morphology with a grass-like structure. As discussed in Chapter 2, the grass formation can be attributed to dislocations in the epitaxial GaN film. This effect arises from rapid recombination due to a high density of dislocations which is up to $10^{12}$ cm$^{-2}$. 
Fig. 3.2 SEM micrographs of PEC-etched GaN samples under different PEC etching times: (a) 1 minute - comparable to as-grown surface; (b) 3 minutes - showing initial roughening; (c) 5 minutes - showing hill-like morphology; (d) 24 minutes - showing grass-like formation. For each case, a 1000 W lamp is used, and a KOH solution concentration of 0.05 M.
As was discussed in Chapter 2, an electrolyte concentration gradient near the sample surface forms during etching. An issue worth considering is whether the concentration gradient can be exploited to suppress rough surface formation. Such an effect might be expected, since the grass “tip” is immersed in a comparatively high concentration solution, as it is at a distance from the rapidly-etching surface. This effect appears to be negligible under the PEC conditions examined, since a mechanism of this type would predict that grass would not form in higher KOH concentration solutions (corresponding to thin solution depletion regions) as readily as low concentration (which have larger depletion regions). In fact, the opposite trend is observed. Consequently, one can conclude that the most decisive factor for the beginning of etching is the photogenerated holes at the surface, with the electrolyte concentration playing a much smaller role.

It has been demonstrated that using lower electrolyte concentrations and higher UV illumination intensity could reduce surface roughness [66]. For comparison, the time evolution of the surface morphology for GaN PEC-etched in lower concentration solution is shown in Figure 3.3.

The trend of surface morphology change in Figure 3.3 is different from that in Figure 3.2. The surface of the GaN PEC-etched in a low concentration electrolyte (0.0025 M KOH) is consistently smoother than those PEC-etched in higher concentration electrolyte (0.05 M KOH). Reduction in electrolyte concentration clearly suppresses the formation of whisker-like surface morphology.
Fig. 3.3 SEM micrographs of PEC-etched GaN samples under different PEC etching times: (a) 5 minute; (b) 15 minute; (c) 30 minute; (d) 60 minute. For each case, a 1000 W lamp is used, and a KOH solution concentration of 0.0025 M.
Figure 3.4 illustrates the mechanism we propose to be responsible for the observed concentration dependence of the surface morphology. The PEC-etch-induced surface oxide is dissolved at a higher rate in higher concentration electrolyte, and slowly dissolved in lower concentration electrolyte. Although in both higher and lower concentration solutions the distribution of holes around dislocations will
produce a selective etching effect between defect-free regions and dislocated regions, the thicker residual oxide present in lower concentration solutions counteracts the selective etching by retarding etching of crystalline material. This feedback produces smoother surfaces in lower concentration electrolyte, but at the expense of reduced etch rate.

As discussed in Chapter 2, it is proposed that higher intensity illumination reduces the difference in etch rates between material near dislocations and crystalline material. Since recombination at defects is characterized by a reduced, but finite, carrier lifetime, the depressed etching rate near defects becomes less pronounced as illumination intensity is increased. Figure 3.5 compares the PEC-etched results obtained with a 1000 W lamp and a 200 W lamp. As shown in Figure 3.5(a) and (b), the density of grass-like structures decreases, and surface morphology improves, with higher intensity of UV illumination. As is noticeable in Fig. 3.5 (c), the surface morphology degrades even with higher intensity illumination if chopped light is used. For Fig. 3.5(c), the shutter in the UV light source was programmed to be open for 1 minute, and then closed for 1 minute, in cycle. Under those conditions, the formed surface oxide has more time to dissolve, leading to rough surface morphology.
Fig. 3.5 SEM micrographs of GaN samples PEC etched in 0.0025 M KOH solutions with (a) illumination intensity of 70-80 mW/cm² for 1 hour; (b) illumination intensity of 350 mW/cm² for 1 hour; and (c) illumination intensity of 350 mW/cm² for 2 hours but with the shutter programmed to be repeatedly open for 1 minute, then closed for 1 minute.
3.3.2 Voltage bias dependence

Figures 3.6(a) and (b) show the surface morphology of GaN samples with doping concentration of $n \sim 6 \times 10^{16} \text{ cm}^{-3}$ and $n \sim 1 \times 10^{18} \text{ cm}^{-3}$, respectively after 30 min PEC etching in 0.005 M KOH solution with no applied bias voltage. From these figures, it can be seen that the surface is rather rough with a grass-like structure. Figure 3.6(c) and (d) are the etched results in low concentration electrolyte (0.0025 M KOH). It is verified again that low concentration produces smoother etched surface, as shown in Figure 3.5.

The dependence of etch rate and etch morphology on applied bias voltage was investigated. Figure 3.7 shows the PEC etching results of GaN samples with doping concentration of $n \sim 6 \times 10^{16} \text{ cm}^{-3}$ in 0.0025 M KOH with +/- 0.65 V and +/- 2 V bias applied. In these images, the Ti metal mask was removed using buffered HF (10:1), followed by $\text{H}_2\text{SO}_4/\text{H}_2\text{O}_2$ (4:1) which can remove the residual surface oxide, but does not change the surface morphology [101]. From Figure 3.7, it can be seen that application of a negative bias between the tungsten tip and Pt cathode does not appreciably improve the smoothness of the etched surface. Applying +0.65 V bias, however, results in a very smooth surface with a root-mean-square surface roughness of approximately 0.5 nm, which is comparable to the unetched original GaN surface (0.4 nm rms roughness).
Fig. 3.6 SEM micrographs of (a) GaN ($n \sim 6 \times 10^{16} \text{ cm}^{-3}$) and (b) GaN ($n \sim 1 \times 10^{18} \text{ cm}^{-3}$) after 30 min PEC etching in 0.005 M KOH; (c) GaN ($n \sim 6 \times 10^{16} \text{ cm}^{-3}$) and (d) GaN ($n \sim 1 \times 10^{18} \text{ cm}^{-3}$) after 30 min PEC etching in 0.0025 M KOH without bias voltage applied.
Fig. 3.7 SEM micrographs of GaN \((n \sim 6 \times 10^{16} \text{ cm}^{-3})\) after 30 min PEC etching in 0.0025 M KOH with bias applied between tungsten probe and Pt cathode, (a) 0.65 V, (b) -0.65 V, (c) 2 V and (d) -2 V.
Fig. 3.8 Etch rate as a function of applied bias for 0.0025 M KOH electrolyte and 350 mW/cm² illumination intensity for lightly doped (6 x 10¹⁶ cm⁻³) and heavily-doped (1 x 10¹⁸ cm⁻³) n-type GaN.

In addition to this change in etched surface morphology, the etch rate is also found to increase with increasing positive bias. Figure 3.8 shows the measured etch rate as a function of PEC bias voltage. As shown in the figure, application of a +2 V bias increases the etch rate by over 200% (from 10 nm/min to 32 nm/min) compared to that for no applied bias. Although still higher etch rates can be obtained at even higher positive biases, the etched surface morphology was observed to degrade for biases > +2 V. On the other hand, application of negative biases clearly suppresses etching. Application of negative biases of more than -2 V was found to roughen the
surface as well as to decrease the etch rate. Comparing Figure 3.7(d) and Figure 3.6(a), the etched surface in a lower KOH concentration solution (0.0025 M) with -2 V bias exhibits nearly the same roughness as the sample surface etched in higher KOH concentration solution (0.005 M) with no applied bias.

Figure 3.9 shows the PEC etching results of GaN samples with a higher doping density of $1 \times 10^{18}$ cm$^{-3}$, in 0.0025 M KOH under +/- 0.65V, and +/- 2 V bias respectively, following the same processing steps after PEC etching as for the lightly-doped GaN samples discussed above. It can be seen that surface roughness and etching rate maintain the same basic trends observed for GaN samples with lower doping of $6 \times 10^{16}$ cm$^{-3}$. However, the etch rate of highly doped material is appreciably lower, as shown in Figure 3.8.
Fig. 3.9 SEM micrographs of GaN (n ~ 1 x 10^{18} cm^{-3}) after 30 min PEC etching in 0.0025 M KOH with bias applied between tungsten probe and Pt cathode, (a) 0.65 V, (b) -0.65 V, (c) 2 V and (d) -2 V.
The open-circuit potential between the W probe (in contact with the Ti mask on the GaN sample) and the Pt cathode was measured. A potential of approximately -0.2 V was measured without UV light illumination, rising to -0.6 V under UV light illumination at an intensity of approximately 350 mW/cm² in 0.0025 M KOH electrolyte. In comparison, the open-circuit potential without a GaN sample inserted was also measured, and was found to be -0.2 V with or without UV light illumination, presumably due to the W-KOH-Pt parasitic electrochemical cell. This phenomenon, in which the open-circuit potential shifts to a more negative value for n-type semiconductors under illumination, has previously been reported in the literature as the “photo-potential” or “photogalvanic” effect [102, 103]. Haisty describes photoelectrochemical etching in dilute electrolytes as an electrochemical process driven by this surface photo-voltage between illuminated areas and dark areas [104]. When an opaque metal mask is used for localized illumination of an n-type semiconductor, the photogenerated holes remain in the illuminated areas to facilitate the oxidation reaction of the semiconductor, while the photogenerated electrons move into the bulk of the semiconductor or the dark areas where they are captured by the contacts and subsequently consumed in reduction of the oxidizing agent. It is expected that any distortion to this electron-hole separation will affect the PEC etch rate and surface morphology. For example, the confinement of photogenerated electrons to the illuminated GaN surface will slow the etching because it increases the recombination probability for holes and thus reduces the effective hole concentration.
Since PEC etching proceeds according to an oxidation-reduction reaction, modifications to the etch chemistry or electrochemical cell to enhance the rate-limiting step can be expected to enhance the etch rate. The observed bias dependence in both etch rate and morphology can be explained by the combination of the “photo-potential” effect and the oxidation-reduction kinetics of the PEC etching chemistry. A two-step reaction model was presented in Chapter 2, which takes into account both the density of photogenerated holes and the electrolyte concentration. In this model, oxidation of GaN at the interface between GaN and electrolyte, enhanced by the photogenerated holes, occurs first. This oxide is then dissolved in the electrolyte to complete the etching reaction, and this dissolution rate of the oxide increases with increasing electrolyte concentration.

This two-step reaction model also explains the observed bias and concentration dependence of PEC etching. Although the residual oxide at the GaN surface impedes further PEC etching, the layer of oxide can assist in maintaining a smooth etched surface by counteracting selective etching between crystalline GaN and defected/dislocated GaN caused by the nonuniform distribution of holes at the surface, consistent with the observed result that etched surfaces are smoother for lower concentration electrolyte compared to higher concentration. Although it is possible in principle to speed the etching while preserving a smooth surface by reducing the spatial variation in the hole concentration at the sample surface through using high illumination intensity to saturate the recombination centers, a more practical alternative is to apply a suitable bias voltage to the PEC cell.
As shown in the experimental setup in Figure 3.1, an applied positive bias voltage helps to extract electrons from the UV illuminated area, leading to further separation of photogenerated electrons and holes, and increases the energy band bending in the GaN near the GaN-electrolyte interface. Thus, a higher concentration of holes is induced at the GaN surface, leading to an increased etch rate while also supplying additional holes to regions where holes are depleted by defect-induced recombination. This results in a more uniform spatial distribution of holes, and results in a smooth etched surface. For negative biases, the opposite effect is produced because holes are shifted by the applied voltage away from the sample surface, resulting in a decreased etch rate. This effect is more pronounced for material with increased donor concentration, possibly due to the smaller density of holes available at the electrolyte-GaN interface at a constant UV illumination intensity. The absorption depth in GaN is about 100 nm at the wavelength of 365 nm, according to the available data in reference [110]. The calculation of the depletion region width ($W_d$) in GaN contacting with KOH electrolyte is similar to the one-sided junction case, $W_d = \sqrt{\frac{2\varepsilon_{GaN}V_{bi}}{qN_d}}$, where $\varepsilon_{GaN}$ is the permittivity of the GaN, $V_{bi}$ is the built-in potential, and $N_d$ is the doping density. The flatband potential of GaN in 0.0025 M KOH electrolyte is about 1.42 V according to section 2.3.2. The calculated depletion region width with no voltage bias applied is approximately 160 nm for a doping density of $6 \times 10^{16}$ cm$^{-3}$, dropping to 40 nm for the doping density of $1 \times 10^{18}$ cm$^{-3}$. According to Fig. 2.6, the electric field in the depletion region drives the
photogenerated holes to the GaN-electrolyte interface. For low-doped GaN samples, the depletion region covers the absorption depth, and all photogenerated holes are driven to the interface if recombination is neglected. For high-doped GaN samples, the absorption depth exceeds the depletion region thickness, and thus only the photogenerated holes in depletion region can be driven by the electric field to the interface, leading to a lower hole density at the electrolyte-GaN interface for this case compared to the lightly-doped samples. Diffusion of holes photogenerated deeper in the GaN bulk is not expected to make a significant contribution to the surface hole concentration since the direction of the concentration gradient (due to the optical absorption profile) favors diffusion away from the surface.

3.4 Conclusions

In summary, we report the bias voltage control of PEC etching for n-type GaN using KOH electrolyte solutions. The etching results in different concentration solutions and under different applied bias voltages are compared and investigated. Lower electrolyte concentrations are shown to improve the smoothness of the etched surface, but at the expense of reduced etch rate. Suitable positive bias voltages applied between the GaN and Pt cathode can enhance the etch rate as well as the smoothness. GaN with a high doping density exhibits slower etch rates and rougher etched surfaces than for lower doped material, but this can be counteracted by selection of an appropriate bias voltage. A two-step reaction model incorporating
electrolyte concentration and density of available holes at the surface is shown to be consistent with the observed results.
CHAPTER IV
DEVELOPMENT OF LATERAL PHOTOOELECTROCHEMICAL ETCHING OF
GALLIUM NITRIDE FOR DEEPLY UNDERCUT STRUCTURES

4.1 Introduction

Gallium nitride and related wide bandgap materials have successfully demonstrated their importance in the area of solid-state devices [1-18]. In addition, the spontaneous polarization, strong piezoelectricity, chemical inertness as well as high temperature stability make them promising candidates for applications in microelectromechanical systems (MEMS). However, the chemical inertness of gallium nitride and related wide bandgap materials also limits the etch techniques that are available, and thus provides motivations for the study of photoelectrochemical (PEC) wet etching, since it overcomes the chemical inertness of GaN and offers the possibility of implementing wet etches for GaN. The ability to achieve the undercut structures and suspended membranes needed for many MEMS and sensor applications by PEC etching would be a significant processing advance, and is the subject of this chapter.

Due to the electrochemical nature of PEC etching, a thin metal film is deposited on the GaN surface to serve as an etch mask as well as the GaN contact electrode. As these masks are optically opaque, GaN under the mask is not normally etched because no holes are photogenerated in these regions, leading to vertical or
near-vertical etch profiles. For forming undercut structures such as cantilevers, which are needed in many novel MEMS, microwave and optoelectronic devices, however, etches that produces a lateral undercut profile are needed. We report two approaches for forming undercut structures by PEC etching: through-wafer illumination and the use of bias-enhanced lateral undercut etching. To the author’s knowledge, this is the first report of bias-enhanced PEC etching of GaN for producing undercut etch profiles.

4.2 Experimental

GaN samples (from TDI, Inc.) with a 3 µm thick GaN layer grown on sapphire substrates by metalorganic chemical vapor deposition (MOCVD) were used. Ti was evaporated on the sample surface and patterned using lift-off to serve as the etch mask, as well as to establish electrical contact to the GaN layer for PEC etching. The GaN samples were mounted in an electrochemical cell containing dilute KOH solution. A 1000 W mercury (xenon) short arc lamp was used as the UV light source, with an intensity of approximately 350 mW/cm². The details of the experimental setup are the same as those described previously.
4.3 Results and discussion

4.3.1 Back-side illuminated PEC etching

The initiation of PEC etching is strongly related to the concentration of photogenerated holes at the semiconductor/electrolyte interface. In conventional front-side illumination PEC etching, an opaque Ti mask blocks the light from entering the region beneath the mask. This leads to etching only taking place in illuminated areas. By contrast, if through-wafer (back-side) illumination is used, the transparent sapphire substrate allows the incident UV light to pass through, and electron-hole pairs are generated uniformly across the wafer, including regions below the Ti mask. Thus, it is possible to get the GaN under the Ti mask to etch laterally and form an undercut profile.

Figure 4.1 shows a scanning electron micrograph of a typical back-side etching result. The GaN sample was immersed in 0.02 M KOH electrolyte for 4 hours which includes 1 hour front-side illuminated PEC etching followed by 3 hours of back-side illuminated PEC etching. When back-side illumination is used, the UV light is incident on the back of the sample through the bottom of the electrochemical cell which holds the sample and KOH electrolyte. In Figure 4.1, clear etch undercut under the Ti mask is observed. Particularly notable is the fact that the remainder of the GaN material under the mask appears with an “inverted pyramid” formation. The same structure formation has also been observed in back-side illuminated PEC selective etching between p-GaN and n-GaN by other researchers [105, 106]. This
under-mask morphology is not well-suited for many applications, but appears to be fundamentally related to through-wafer illumination PEC etching.

In particular, the GaN films grown on sapphire by MOCVD or HVPE usually exhibit Ga-face polarity, and N-face polarity is obtained either on the back-side of such layers after being lifted off from the substrate or by tuning the polarity in MBE growth with a thin AlN buffer layer [107]. Consequently, the back-side PEC etching sees N-face polarity for the samples used in this work. Pyramid structures have previously been reported on N-face polarity GaN [69, 70].

Fig. 4.1 Scanning electron micrograph of back-side illuminated PEC-etching of GaN.
It has been demonstrated that smooth etched surfaces can be obtained using low electrolyte concentration and high UV intensity illumination. In this through-wafer illumination configuration, however, the effective illumination intensity at the GaN/electrolyte interface is low due to absorption as the UV light passes through the GaN layer before reaching the GaN-electrolyte interface, making it more difficult to control the surface morphology by way of increased illumination intensity.

4.3.2 Front-side illuminated PEC etching

As previously discussed in Chapter 3, externally applied voltage bias can increase the etch rate as well as improve the smoothness of etched surfaces [108, 109]. Bias-enhanced PEC etching is also shown for the first time to allow for the formation of lateral undercut profiles with a longer etching time. Figure 4.2 shows the etch profile obtained after PEC etching in 0.025 M KOH for 4 hours with an optical intensity of 350 mW/cm$^2$ and 2 V voltage bias applied between the GaN samples and the Pt cathode. As shown in Figure 4.2(a), a suspended Ti metal bridge forms due to etch undercut. From our previous PEC etch studies, a vertical etch profile would have been obtained for an unbiased etch. Particularly notable is the fact that the lateral extent of the etch is fairly regular and uniform, and the morphology in the undercut regions is smoother than for back-side illumination. Figure 4.2(b) shows a higher magnification view of another cantilever structure. From the figure, the lateral etching property for GaN under Ti mask is clearly shown. The lateral etched extent is
quite uniform – about 2 µm around the edge of Ti metal for these etch conditions and
duration, and is comparable to the vertical etch depth. Also, no apparent “inverted
pyramid” morphology can be detected, in contrast to back-side PEC etched samples.

For comparison, GaN samples etched under identical process conditions
except without voltage bias are shown in Figure 4.3. No significant lateral etching
can be observed. The GaN under the Ti mask clearly remains after PEC etching, and
the sidewall surface is rather rough and striated. These striations appear to arise from
some very limited lateral etching, with an extremely high density grass-like
morphology.

This bias-enhanced PEC process can also be used for release of structures.
Although Figure 4.2(b) shows residual GaN under the Ti cantilever, it can be fully
removed by increased PEC etching time. Figure 4.4 shows the result of PEC etching
under the same conditions as Fig 4.2(a), but for 75% longer etch time (7 hours). The
GaN under the cantilever is totally removed, and the suspended Ti cantilever is fully
released.
Fig. 4.2 SEM micrographs of (a) suspended bridge structure; (b) suspended cantilever structure, with front-side illumination and voltage bias.
Fig. 4.3 SEM micrographs of (a) bridge structure, and (b) cantilever structure with front-side illumination and no voltage bias applied.
4.3.3 Discussion

Previous studies have shown that KOH solutions have no etching effect on GaN in the absence of UV illumination and that the concentration of holes at the semiconductor surface and the concentration of the KOH electrolyte are critical parameters in controlling the PEC etch. As discussed in previous sections, the PEC etching of GaN in KOH solutions is a photoassisted oxidation-reduction reaction, with oxidation facilitated by holes at the surface and reduction by OH\(^{-}\). For the case of bias-enhanced PEC etching to form an undercut profile, the same fundamental
principles apply. While the details of the etch rate enhancement are not fully understood, the following mechanism is proposed. Although the metal mask blocks the UV light and thus prevents photogeneration of holes under the mask, the spatially nonuniform generation rate leads to a carrier concentration gradient. A key distinction, however, is that the applied bias (positive on Ti mask, negative on the Pt electrode), acts to attract OH\(^-\) ions to the masked areas, leading to a local increase in effective electrolyte concentration. This increases the etch rate in the region below the mask and allows the dissolution of the striated material beneath the mask (as shown in Fig. 4.3). A schematic illustration of this mechanism is shown in Figure 4.5.

Fig. 4.5 Schematic drawing of applied voltage effect on ion OH\(^-\).
4.4 Conclusions

In conclusion, we report the development of lateral photoelectrochemical etching of GaN for the fabrication of deeply undercut structures. Normal front-side illuminated PEC etching without voltage bias applied was found not to etch the GaN in regions masked by Ti and no undercut structure can form. Although through-wafer backside-illuminated PEC etching can be used to shine light through the transparent sapphire substrate and photogenerate electron-hole pairs in the GaN under the Ti mask, the etched results are not uniform, and an “inverted pyramid” GaN morphology results. Use of an applied voltage bias was found to enhance the lateral PEC etching of GaN in front-side illuminated PEC etching. With a sufficient etch time, suspended Ti cantilevers were fully released after uniformly and totally removing the GaN under the cantilevers. This is the first reported observation of this effect; a simple explanation for this effect has been proposed.
CHAPTER V

DEVELOPMENT OF SUSPENDED DIELECTRIC AND SEMICONDUCTOR MEMBRANE STRUCTURES

5.1 Introduction

As described in previous chapters, GaN offers promising material properties for sensors, optoelectronics, and electronic devices. The chemical inertness of GaN also makes processing, and in particular the formation of suspended membrane structures, more challenging. The use of PEC etching to fabricate free-standing membranes has been investigated. In particular, this research has resulted in the first successful report of free-standing of AlGaN membranes formed by wet-chemical processing. A key development that enables the formation of wide-bandgap semiconductor membranes (as opposed to the metallic membrane in Chapter 4) is bandgap-selective or wavelength-selective etching. An investigation of the formation of suspended insulating dielectric membranes (e.g. SiO₂) is also described.
5.2 PEC etching of SiO$_2$/GaN and formation of suspended SiO$_2$ membranes

5.2.1 Experimental

In addition to the formation of undercut metallic structures demonstrated in Chapter 4, for some applications free-standing dielectric membranes are needed. Formation of undercut SiO$_2$ membranes on GaN by PEC etching has been investigated.

![Microscope image of SiO$_2$/GaN/Sapphire sample before PEC etching.](image)

Fig. 5.1 Microscope image of SiO$_2$/GaN/Sapphire sample before PEC etching.

For the fabrication of dielectric membranes, a layer of SiO$_2$ 400 nm thick was deposited by PECVD on the surface of GaN samples made from material of type 2 (see Table 2.1). Then, AZ5214E photoresist was spun on top of the SiO$_2$ and
patterned using photolithography. The exposed SiO$_2$ was etched away by RIE in CF$_4$ plasma to create the mask pattern. GaN is impervious to RIE under the conditions used to etch the SiO$_2$. Finally, a layer of Ti was patterned, deposited, and lifted off on the top to form a suitable electrical contact for PEC etching. The metallization pattern is the same as that of SiO$_2$ because the same photolithography mask was used for simplicity, but a misalignment was intentionally used to create the offset pattern shown in Figure 5.1.

SiO$_2$ is expected to be almost transparent to UV light since the bandgap energy of silicon dioxide is about 9 eV, which is much larger than the energy of photons with a wavelength of around 365 nm. A schematic illustration of the formation of a membrane is shown in Figure 5.2. With the UV light passing through the transparent SiO$_2$ mask, pairs of electrons and holes are created both in the uncovered regions as well as the regions beneath the SiO$_2$ film. At first, GaN material near the edge of the SiO$_2$ features is etched away. As the etch proceeds, a cavity forms below the SiO$_2$ and stops at the edge of the Ti mask which blocks the UV light. Given a long enough time, PEC etching will take place wherever holes are photogenerated and the solution can reach.
Fig. 5.2 Schematic illustration of the formation of a suspended membrane by PEC etching with a transparent mask; (a) before PEC etching; (b) after PEC etching.
5.2.2 Results and Discussion

Based on experience from previous experiments, the concentration of the KOH solution was set to 0.005 M in order to obtain the combination of an appreciable etching rate while maintaining a smooth etched surface. Because it was found that the use of KOH solution post-treatment at elevated temperature plays an important role in dissolution of gallium oxide, the solution was heated to 80 °C during the PEC etching process. The light intensity was set to 200 mW/cm², and the duration of the etch was 3 hours.

Fig. 5.3 Optical image of SiO₂/GaN/Sapphire sample after PEC etching with transparent SiO₂ mask.

Figure 5.3 shows an optical micrograph of the resulting structure. In comparison with Figure 5.1 before etching, the color around the discrete rectangular
SiO$_2$ patterns is clearly changed, indicating that an air cavity has formed under the SiO$_2$. This can also be observed by SEM, as shown in Figure. 5.4.

In Figure 5.4(a), the suspended membrane is clearly visible. Because the membrane is pinned by metal on both sides, tension in the SiO$_2$ deforms the free-standing film. Under the membrane, the GaN is not etched away cleanly, compared with the areas outside the masked area. This may be due to the limited diffusion of the solution in this cavity, reducing the etch rate. For comparison, a GaN region under an opaque Ti mask on the same sample is also shown in Figure 5.4(b). As can be seen, the lateral etching is very limited for this case. Figure 5.4(c) shows the cantilever structures after PEC etching. Because one end of the structure is free, the cantilever structure does not deform as dramatically as Figure 5.4(a), but clearly sags toward the substrate.

Another interesting point in this modified PEC etching at elevated temperature is the higher etching rate. With the temperature of the solution increased from room temperature to 80 °C, we found that the etching rate increases from 35.5 Å/min to 300 Å/min in the same concentration of KOH solution, i.e. 0.005M, and illumination intensity. The etching rate is clearly enhanced, and at the same time, the smoothness of the etching surface (at least in open-substrate area) is not compromised significantly.
Fig. 5.4 SEM micrograph of PEC etching of SiO$_2$/GaN samples: (a) SiO$_2$ suspended membrane pinned by Ti mask on both sides; (b) GaN under Ti opaque mask on the same sample for comparison; and (c) SiO$_2$ cantilevers.
Figure 5.5 shows the same type of samples, PEC etched under the same etching conditions as in Figure 2.21, but with a tilted etching setup as shown schematically in Figure 2.20, and immersed in 0.5 M stirred boiling KOH solution for 30 minutes after PEC etching. As expected, Figure 5.5 shows a tilted etch profile is attained. Also, the surface is found to be smoother than in Figure 2.21. The reason for this improved morphology may be that the electrolyte concentration under the SiO$_2$ mask is lower due to the limited ability of KOH to diffuse into this confined space beneath the mask.

Fig. 5.5 SEM micrograph of PEC etching of SiO$_2$/GaN samples with tilted setup.
5.3 PEC etching of AlGaN/GaN/Sapphire and formation of suspended semiconductor membranes

5.3.1 Experimental

For some applications, the formation of thin semiconductor membranes or cantilevers is an essential fabrication capability. Efforts to realize such structures using PEC etching were developed and demonstrated.

![Fig. 5.6 Schematic of sample and experimental setup.](image)
The samples used for this investigation consist of a ~1.2 µm GaN layer grown on c-plane sapphire substrates by metalorganic chemical vapor deposition (MOCVD), followed by a ~0.2 µm thick Al$_{0.38}$Ga$_{0.62}$N layer. A layer of 150 nm Ti metal was deposited on the sample surface by electron-beam evaporation and patterned using lift-off to be used as the etch mask. The schematic of the sample structure is shown in Figure 5.6. The detail of PEC etching experimental setup was described in the previous chapters. The optical properties of GaN and AlGaN materials are shown in Fig. 5.7 [110].

Fig. 5.7 (a) Cathodoluminescence for Al$_x$Ga$_{1-x}$N samples; (b) absorption coefficients for Al$_x$Ga$_{1-x}$N samples. [110]
5.3.2 Results and Discussion

At first, an unfiltered front-side illumination was used with PEC etch to transfer the Ti metal pattern through the Al$_{0.38}$Ga$_{0.62}$N/GaN structure. The bandgap of Al$_{0.38}$Ga$_{0.62}$N is about 4.24 eV (see Fig. 5.7 [110]), corresponding to wavelength of 292 nm. The bandgap of GaN is 3.4 eV, and the corresponding wavelength is 365 nm. In this experimental step, the PEC etch is non-selective between Al$_{0.38}$Ga$_{0.62}$N and GaN, because the wavelength range emitted from the arc lamp source is from 200 to 2500 nm (see Appendix A), which can photogenerate electron-hole pairs in both materials.

Figure 5.8 (a) and (b) show the PEC etching results in 0.002 M KOH solution after 10 hours of etching. In Figure 5.8, no clear etched step near the Ti metal mask can be seen, but fissures in the AlGaN layer can be seen, along with evidence that the bulk GaN material beneath the AlGaN layer has been etched away (Fig. 5.8(b)). A possible explanation for this effect is that the KOH electrolyte is not an effective electrolyte for PEC etching of AlGaN, since KOH solution cannot as readily dissolve the Al oxide that forms during PEC etching. To overcome this obstacle, high concentration KOH solutions (0.02 M) were evaluated. After 2 hours of etching, the results in Figure 5.8(c) were obtained. High concentration solution can clearly etch the AlGaN/GaN heterostructure, but with a rough, grass-like surface structure.
Fig. 5.8 SEM micrographs of PEC-etching results: (a) in 0.002 M KOH solutions, and (b) is the magnification of (a); (c) in 0.02 M KOH solution.
As an alternative, H$_3$PO$_4$ was evaluated for the electrolyte, since it is effective at dissolving Al oxides. The PEC etching result is shown in Figure 5.9. The samples were PEC etched in $p$H=3 H$_3$PO$_4$ solution for 2 hours. From Figure 5.9, one can clearly see the Ti, AlGaN and GaN layers in the structure. It can be concluded that H$_3$PO$_4$ is an effective electrolyte solution for PEC etching of AlGaN.

After PEC etching of both AlGaN and GaN, the samples were put in H$_3$PO$_4$:H$_2$O (1:3) solution for 30 minutes to remove any residual surface oxide, then cleaned by acetone, 2-propanol, and deionized water.

![Fig. 5.9 SEM micrograph of PEC-etching results in $p$H=3 H$_3$PO$_4$ Solution.](image)

A subsequent filtered, backside-illuminated PEC etch process was used. Bandgap selective PEC etching requires that the incident light pass through the wide
bandgap materials – for example, sapphire and AlGaN - and selectively excites electron-hole pairs in the narrow bandgap material – GaN. This requirement is fulfilled with the use of an optical band pass filter. For our experiment, a filter with a minimum peak transmission of 40%, center wavelength of 355 nm, and full width at half maximum of 10 nm was used. For through-wafer backside illumination, filtered UV light passes through the sapphire, and electron-hole pairs are selectively photogenerated only in the GaN film, both in masked and unmasked areas. The AlGaN layer on top of the GaN is negligibly influenced by the filtered light, because the bandgap of Al$_{0.38}$Ga$_{0.62}$N is 4.24 eV, and the energy of incident photons after filtering is not enough to generate electron-hole pairs. To release the AlGaN membrane, a low concentration KOH solution (0.0025 M) was used, since this has been shown to result in smooth etch morphologies in Chapter 3. No voltage bias was applied and the etching time is 2 hours. After the photoelectrochemical bandgap-selective etch, the Ti metal was removed with buffered HF (10:1), using care while rinsing and drying the samples because the thin AlGaN film is very fragile.
Figure 5.10 is a typical etch result examined by SEM, showing that a thin suspended AlGaN film has been formed. It can be observed from Figure 5.10 that the etched GaN surface is not smooth, especially under the suspended AlGaN membrane where the density of grass-like structures is higher. Previous experiments show, however, that this combination of light intensity and solution concentration produces smooth etched surfaces under conventional front-side illumination conditions. This roughness arises from the lowered surface hole concentration due to absorption as the light passes through the sapphire and GaN before reaching the GaN-electrolyte interface, as described in Chapter 4. It is noted that the inverted pyramid formation is not observed under these etching conditions. The cause may come from several sources. The thickness of the GaN layer under the AlGaN layer used here is about
~1.2 µm, which is less than the thickness of the GaN material used in Chapter 4 in which inverted pyramids were observed. Therefore, the reduction of light intensity in the thin layer is significantly less than for the thick layer used in Chapter 4 for backside illuminated PEC etching. In addition, the GaN layer used here has doping density of 4x10^{18} cm^3, compared with material type 2 in Table 2.1 which is unintentionally doped with a background doping concentration of 10^{16} cm^3. The effect of spontaneous polarization in GaN may decrease in material with large concentration of free carriers, which may also suppress the formation of pyramids.

Front-side illuminated bandgap-selective PEC etching was also investigated for releasing a membrane. After etching through both the AlGaN and GaN using broadband non-selective PEC etching, the Ti mask was removed by buffered HF, and then the sample was etched in 0.0025 M KOH solution with front-side filtered illumination for 90 minutes. The results are shown in Fig. 5.11, in which a membrane structure is clearly evident. One part of the membrane has cracked, revealing a grass-like morphology underneath the membrane. The density of grass-like structures is dramatically lower beyond the membrane area, although the etched surface is not smooth. As discussed previously, the observed difference in surface morphology suggests that either the solution concentration or the density of photogenerated holes are different in the “open” and AlGaN membrane-covered regions. Due to surface reflection of light from the AlGaN, the most likely explanation is a reduced optical intensity beneath the membrane.
Fig. 5.11 SEM images of AlGaN membrane fabricated by front-side illuminated bandgap-selective PEC etching between AlGaN and GaN.
A concentration gradient would not explain the observed morphology, since a lowered concentration (as one would expect in a confined space beneath the membrane) is associated with smoother, rather than rough, morphology. As discussed in Chapter 1, polarization effects can increase or decrease interfacial free carrier concentrations in AlGaN/GaN. For our samples, the piezoelectric polarization effect caused by the coherently strained Al$_x$Ga$_{1-x}$N on a GaN substrate, has the same sign as the spontaneous polarization for Ga-face material. The sign of the polarization produces a potential gradient for electrons moving down from the AlGaN surface towards the AlGaN/GaN interface, and drives electrons towards the two-dimensional electron gas (2DEG) that forms at this interface. Although this kind of effect is possibly reduced by the presence of dislocations in the AlGaN layer and/or the high concentration of free carriers in the GaN layer, it may still suppress the accumulation of holes at the interface, leading to a rough surface with a high density of grass-like structures.

In Chapter 4, the formation of Ti/GaN undercut structures was demonstrated. It has been found that use of a suitable voltage bias during etching will enhance the degree of lateral etching, resulting in the formation of undercut structures by etching away GaN under the Ti metal mask. The possibility of using this approach to form free-standing AlGaN membranes was also investigated. To form these structures, the same non-selective PEC etching process described previously was used to transfer the Ti metal pattern to the AlGaN/GaN. Then, the sample (with Ti metal in place) was PEC etched with front-side filtered illumination, with a 2 V bias applied between the
GaN sample and Pt cathode. A KOH electrolyte concentration of 0.0025 M, and etching time of 4 hours were used.

The etched result is shown in Figure 5.12. It is clearly observed that an AlGaN cantilever is successfully fabricated, and that the enhanced lateral etching caused by voltage bias (as discussed in Chapter 4) enables the fabrication of free-standing structures.

![Figure 5.12 Front-side illuminated PEC etching of AlGaN and GaN, with 2 V voltage bias and filter.](image)

The causes for the observed separation of the Ti metal from the AlGaN are not entirely understood. It may be the result of poor adhesion between the AlGaN and Ti metal after long etching time, perhaps combined with a local temperature increase during PEC etching due to the high illumination intensity and the different thermal expansion coefficients between AlGaN and Ti metal. Further investigation are required to understand this effect in detail.
5.4 Conclusions

In summary, released dielectric SiO$_2$ membranes on GaN were fabricated and demonstrated using PEC etching. UV light allows electron-hole pairs to be photogenerated in the GaN underneath the SiO$_2$, leading to selective PEC undercut etching of the GaN. Fabrication of AlGaN semiconductor membranes has also been demonstrated, using bandgap-selective PEC etching between AlGaN and GaN. These processes are promising for fabrication of sensors and other MEMS devices and structures.
CHAPTER VI
MICROMACHINING ENABLED POWER SENSOR-DESIGN AND SIMULATION

6.1 Novel inline transmissive microwave power sensor

The fabrication processes demonstrated in Chapters 2-5 allow the fabrication of structures in GaN-based heterostructures with controlled surface morphology, etch rate, etch profile, and degree of lateral undercut etching. Bandgap-selective etching, as well as membrane release etches based on through-wafer and bias-enhanced etching have also been demonstrated. These processes are promising for enabling new types of devices and sensors in the GaN-based material system. As one example of a new device enabled by these fabrication processes, a novel microwave power sensor has been investigated theoretically. This novel sensor is enabled by the ability to micromachine GaN and related materials, and may offer several advantages over conventional power sensor designs.

For conventional power sensors, a diode or bolometer is used to measure the power incident on the detector. To use such a device in a system to monitor power levels non-invasively, electromagnetic coupling structures are required to extract a fraction of the transmitted power from the system being measured and steer it to the detector for measurement. The losses due to these couplers often limit system performance and can also limit the frequency of operation. In addition, many
conventional coupler designs are bulky and can not be easily integrated with electrical devices, resulting in more complex assembly and larger physical size. A monolithically integrated sensor with good return loss over a broad bandwidth is therefore highly desirable. The ability to micromachine GaN and related materials may enable the fabrication of an inline transmissive microwave power sensor with low input reflection coefficient. This sensor design appears promising for integration into a micromachined low-loss coplanar transmission line, allowing for the monitoring of the microwave power along the transmission line, and is particularly well suited for the GaN material system, since GaN is widely applied to high power microwave electronics.

The design parameters of this sensor approach have been explored, and theoretical projections of performance obtained. Due to the unavailability of a suitable heterostructure, experimental verification has not been attempted. Instead, a comprehensive theoretical evaluation of the design has been performed to evaluate the performance limits attainable with this device concept.

The physical structure of the micromachined sensor is illustrated schematically in Figure 6.1. In the schematic, the two ground planes of the coplanar waveguide (CPW) are suspended above the substrate, forming air bridges. Under the ground planes, thermopiles are fabricated on the top of the AlGaN membrane created by PEC etching. The main principle of operation for the sensor is based on the Seebeck or thermoelectric effect. In this sensor design, the ohmic loss in the center conductor of the coplanar waveguide transmission line creates a temperature gradient
across the micromachined membrane and the thermopiles. Because of the Seebeck effect, a voltage develops across each thermopile. The thermopiles are connected electrically in series to increase the sensitivity of the sensor. The total output voltage can be measured and calibrated to extract the amount of power transmitted through the line. Sensors based on this concept have been previously demonstrated in the GaAs/AlGaAs material system [51, 111, 112], but the lack of suitable fabrication processes has prevented them from being developed in the emerging GaN/AlGaN system.

Fig. 6.1 Schematic illustration of the structure of power sensor.
A key enabling element of this device is the suspended membrane. The suspended membrane in the power sensor design is used to enhance the sensitivity and response time of the power sensor by reducing the total thermal capacitance and increasing the thermal resistance. In addition, the air cavity under the membrane decreases the dielectric loss and further improves the performance of the sensor. The insertion loss in a coplanar waveguide transmission line can be expressed as follows:

\[
IL(dB) = -10 \log \frac{P_{out}}{P_{in}} \quad \text{(Eq. 6.1)}
\]

In general, this loss includes metallic loss, dielectric loss, surface wave loss, and radiation loss. In the case of a CPW-based power sensor, such as the design shown in Figure 6.1, the first two losses account for the majority of the total loss [113]. Because of the air cavity formed under the membrane, the dielectric loss can be made very small, and so the metallic loss will be the biggest constituent. This metallic loss will heat up the center conductor, leading to a temperature gradient across the membrane that is sensed by the thermopiles. Thus, from the measured Seebeck voltage of the thermopiles, the amount of RF power dissipated due to the metallic loss can be determined, and the input power can be extracted precisely.
6.2 Seebeck effect in GaN

The electrons in semiconductors carry both charge and energy, so temperature gradients can produce electrical effects. For example, when two contacts to a semiconductor are held at different temperatures, a potential difference develops in the circuit connecting the two contacts. This effect is known as the Seebeck effect. A schematic drawing of the energy diagram for an n-type semiconductor in the presence of a temperature gradient is shown in Figure 6.2 [114].

![Fig. 6.2 Schematic drawing illustrating the Seebeck effect.](image-url)
Because the Fermi level in a semiconductor is a function of temperature, the values of $E_c - E_f$ are different at the two metal-semiconductor junctions as shown in Figure 6.2. This results in a carrier concentration gradient along the semiconductor. If the contacts are open-circuited, the diffusion component of the current (due to the carrier gradient) must be balanced by the internal electric field, since the current is zero under open circuit conditions:

$$J = q\mu_e n_e + q \frac{d}{dx} (D_e n) = 0 \quad \text{(Eq. 6.2)}$$

where $J$ is the current density, $\mu_e$ is the electron mobility, $n$ is the electron density, $\epsilon$ is the electric field, and $D_e$ is the diffusion coefficient. From equation 6.2, we obtain:

$$\epsilon = -\frac{1}{\mu_e n} \frac{d}{dx} (D_e n) \quad \text{(Eq. 6.3)}$$

At the same time, $D_n$ can be expressed as:

$$D_e = \frac{kT}{q} \mu_e = \frac{AB^c}{m} (kT)^{c+1} \quad \text{(Eq. 6.4)}$$

where $\mu_e = \frac{q\tau}{m}$ and $\tau = A\epsilon^c$. The value of $c$ changes from $-3/2$ for lattice scattering to $1/2$ for impurity scattering [114]; $\epsilon = BkT$ because the average kinetic energy of electrons is proportional to $kT$. 

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As discussed above, the Fermi level is a function of temperature, following the Boltzmann distribution:

\[ n = N_c \exp\left(\frac{E_F - E_c}{kT}\right) \quad (\text{Eq. 6.5}) \]

and so,

\[ \frac{d(E_c - E_F)}{dT} = \frac{E_c - E_F}{T} + \frac{3k}{2} \frac{kT}{n} \frac{dn}{dT} \quad (\text{Eq. 6.6}) \]

Combining Equations 6.3, 6.4 and 6.6, one can find the Seebeck voltage \( \Delta V \) and Seebeck coefficient \( S_n \) [114]:

\[ \Delta V = -\frac{kT}{q} \left[ (E_c - E_F) + kT (\frac{5}{2} + c) \right] \Delta T = S_n \Delta T \quad (\text{Eq. 6.7}) \]

The Seebeck coefficient, \( S_n \), depends on the material band structure through the carrier effective mass. One calculation based on the band structure details for GaN is given by [115]:

\[ S_n = -\frac{K}{q} \left[ \ln \left( \frac{nh^3}{2(2\pi KTm^*)^{1/2}} \right) + \left( \frac{5}{2} + m \right) \right] \quad (\text{Eq. 6.8}) \]
Using this expression, the Seebeck coefficient is expected to be a fairly large 386 µV/K for $n = 10^{17} \text{ cm}^{-3}$ GaN [115]. This compares favorably with other common semiconductors that are used in thermopile applications. In addition, it has been shown in the GaAs/AlGaAs material system that the Seebeck coefficient increases with Al mole fraction, as shown in Figure 6.3 [116, 117]. A similar trend is expected for AlGaN, providing a path for optimizing the thermopile performance.

Fig. 6.3 Dependence of the Seebeck coefficient on AlAs molar fraction in the GaAs/AlGaAs material system. [116]
6.3 Thermal design and analysis

For the power sensor depicted in Fig. 6.1, control over the heat flow in the structure is an important design consideration. To analyze this, one can think of the heat flow, \( q \), as being proportional to the quotient of the driving force, \( \Delta T \), and the thermal resistance, \( R_{th} \):

\[
q = \frac{\Delta T}{R_{th}} \quad \text{(Eq. 6.9)}
\]

\[
R_{th} = \frac{l}{Kwt} \quad \text{(Eq. 6.10)}
\]

where \( q \) is the heat flow (heat per unit time), \( \Delta T \) is the difference in temperature between two locations, \( K \) is the thermal conductivity of the constituent material, and \( l, w, \) and \( t \) are the length, width, and thickness respectively.

There are three primary criteria to define the performance of a thermoelectric power sensor, i.e., the responsivity \( R_s \) which is the ratio of output voltage to incident power, the thermal time constant \( \tau \) which is the response time of the sensor, and the noise equivalent power \( \text{NEP} \). The figures of merit can be expressed as:

\[
R_s = \alpha N S R_{th} \quad \text{(Eq. 6.11)}
\]

\[
\tau = C_{th} R_{th} \quad \text{(Eq. 6.12)}
\]
\[ \text{NEP} = \frac{1}{R_s} \sqrt[4]{4k_b R_e T \Delta f} \]  
\text{(Eq. 6.13)}

In these expressions, \( \alpha \) is the absorption coefficient, \( N \) is the number of thermopiles, \( S \) is the Seebeck coefficient, \( R_{th} \) is the thermal resistance of the sensors, \( \Delta f \) is the bandwidth, \( k_B \) is Boltzmann’s constant \( = 1.38066 \times 10^{-23} \) J/K, \( R_e \) is the electrical resistance of the sensor, and \( C_{th} \) is the thermal capacitance of the sensor. In equation 6.13, it is assumed that thermal noise accounts for majority of the noise, i.e.

\[ \langle V \rangle = \sqrt{4K_B R_e T \Delta f} . \]

To maximize the detector responsivity, \( R_{th} \) and \( S \) should be made as large as possible. By using a membrane structure instead of a solid bulk substrate, the thermal resistance increases following Equation 6.10. However, this is limited in practice by the extreme fragility of a very thin membrane. As a compromise, a thickness of 1 \( \mu \)m has been assumed for analysis. At this thickness, the membrane is expected to be sufficiently stable and robust mechanically, while still increasing the thermal resistance significantly. Insufficient mechanical experimental data is available at present to rigorously optimize the membrane thickness.

An additional trade-off in sensor design exists between the responsivity \( R_s \) and the time constant \( \tau \). A minimization of the response time implies a reduction of the thermal resistance which will decrease the responsivity. Theoretically, an infinitely long thermopile can produce the maximal Seebeck voltage. However, as in the discussion above, a long response time would result. In practice, a small \( \tau \) is desirable, since in this case the sensor can more rapidly respond to changes in
incident power, and the potential reduction in responsivity can be made up by electronic amplification of the output signals.

For the micromachined inline microwave power sensor, the heat produced by ohmic loss in the center conductor of the CPW flows partly through the thermopiles by conduction and partly through the ambient environment by convection or radiation. This can be modeled as a thermal equivalent lossy transmission-line model, as shown in Fig. 6.4. The thermal resistance (per unit length) of the thermopile/membrane is $R$, and the thermal conductance (per unit length) is $G$ due to radiation and convection.

Fig. 6.4 Schematic cross-sectional diagram of suspended membrane and thermopile sensor with electrical analogue of the thermal circuit; because of symmetry, only half of the sensor structure is shown.
Following the same methodology as in the work of Volklein and Herwaarden, et al. [118, 119], suitable sizes of the thermopiles for this sensor are estimated. As shown in Figure 6.4, it is reasonable to assume that the temperature $T_1$ is uniform under the center conductor of the CPW due to the high thermal conductivity of the center conductor metal, and the temperature $T_0$ near the end of the membrane is also uniform and equal to the ambient temperature due to the large substrate mass. According to Fourier’s law of heat transfer, we can derive the following expression [118-120]:

$$d^2 \Delta T \over dx^2 - r^2 \Delta T = 0$$  \hspace{1cm} \text{(Eq. 6.14)}$$

with the boundary conditions,

$$\Delta T \vert_{x=0} = T_0 - T_0 = 0$$  \hspace{1cm} \text{(Eq. 6.15)}$$

$$\frac{d \Delta T}{dx} \vert_{x=L} = q(L)R$$  \hspace{1cm} \text{(Eq. 6.16)}$$

where $r^2=RG$, and $q(L)$ is the heat flow in the thermopiles.

The solution of equations 6.14, 6.15 and 6.16 is given in equation 6.17:

$$\Delta T(x) = \frac{q(L)R \sinh(rx)}{r \cosh(rL)}$$  \hspace{1cm} \text{(Eq. 6.17)}$$
Combining equations 6.9 and 6.17, the total thermal resistance of the thermopile $R_{tp}$ is,

$$R_{tp} = \frac{T_i - T_0}{q(L)} = \frac{R}{r} \tanh(rL)$$

(Eq. 6.18)

If the loss of the heat around the center conductor area in the CPW is also considered in addition to the heat flow $q$ incident on the thermopiles, the total heat flow $Q$ created by the metallic loss should be the sum of both heat flow terms. Let $R_f$ be the thermal resistance associated with the thermal loss of the center conductor area, due to the convection and radiation losses from the center conductor. The total thermal resistance of the sensor $R_{th}$ can be expressed as:

$$R_{th} = R_{tp} \parallel R_f = \frac{R}{r} \tanh(rL) \parallel R_f = \frac{T_i - T_0}{Q}$$

(Eq. 6.19)

For a long thermopile, $L \to \infty, R_{tp,\text{max}} = \frac{R}{r}$, and the total thermal resistance $R_{th}$, the responsivity $R_s$, and the time constant $\tau$ are all maximized. If we define $\frac{R_f}{R_{tp,\text{max}}} = m$, we can express the thermal resistance and responsivity relative to their maximal values:
The electrical resistance of the sensor $R_c$ is also proportional to the length of the thermopile, according to $R_c = \frac{L}{W}$ where $W$ is the average cross-sectional area and $\rho$ is the average electrical resistivity of the thermopiles. The noise equivalent power NEP can be expressed as follows:

$$NEP = \frac{1}{R_i \sqrt{4K_B R T \Delta f}} = \frac{1}{\alpha N S} \sqrt{\frac{4k_B \rho}{W \Delta f} \frac{L}{m \tan(rL)}} \left[ \frac{R}{r} \frac{m \tan(rL)}{m + \tan(rL)} \right]$$

(Eq. 6.21)

According to Equation 6.21, the NEP at first decreases with increasing length of the thermopile, then reaches a minimum value followed by increasing noise equivalent power as the thermopile length is increased beyond this point. The trends of the responsivity and the inverse of noise equivalent power as a function of thermopile length of the thermopiles are shown in Figures 6.5 and 6.6. As can be seen in Fig. 6.5, sensor responsivity improves with increasing thermopile length. Fig. 6.6, however, shows that NEP has a clear optimum, which shifts with the amount of radiation loss. In most applications, design for best NEP is preferred with the potential reduction in responsivity made up by electronic amplification of the output signals.
Fig. 6.5 The dependence of the relative responsivity $R_s(rL)/R_{s,max}$ on relative thermopile length $rL$.

Fig. 6.6 The dependence of the relative inverse noise equivalent power $\text{NEP}_{\text{min}}/\text{NEP}(rL)$ on relative thermopile length $rL$. 
An additional set of design considerations that must be considered comes from the need to incorporate the thermopiles within a CPW structure. Because the characteristic impedance of this sensor should be matched to the CPW feed line to insure low reflection loss, we cannot determine the size of the sensor or the value of $m$ from the above thermal considerations alone; the electromagnetic simulation of the sensor’s CPW structure will place additional constraints on the sensor geometry. Thus, the performance of the sensor can be estimated and then optimized only through a careful analysis considering thermal as well as electromagnetic effects.

### 6.4 Electromagnetic design and simulation

When the inline transmissive microwave power sensor is inserted in a CPW line to monitor the transmitted power, its influence on the CPW line should be as small as possible. In many cases, this means that the sensor’s characteristic impedance should be designed to be nearly 50 $\Omega$ over a wide frequency band, thus minimizing the reflection loss from the sensor.

The locus of an impedance or admittance function for a transmission line when plotted on a Smith chart is a spiral for a lossy line, or a circle for a lossless line. The center of the spiral or the circle is the transmission line’s characteristic impedance normalized to 50 $\Omega$. Using the characteristic impedance of the sensor as a design goal, the suitable size for the power sensor can be derived. The IE3D software package from Zeland Inc. was used to simulate the electromagnetic field distribution.
and characteristic impedance of the structures needed in the sensor [121]. The substrate layouts of a standard CPW and a suspended-ground metallization with a thin membrane CPW used during the simulation are illustrated in Figure 6.7.

Fig. 6.7 Schematic illustration of the cross-sectional structure of (a) standard CPW, (b) suspended-ground metallization with a thin membrane CPW.
For the electromagnetic analysis, the thicknesses are 0.013 inch, 3 µm and 1 µm for sapphire, GaN and AlGaN, respectively. The height of the air gap below the ground metallization was set to 3 µm by considering that a thickness in this range can be fairly simply achieved using sacrificial photoresist and lift-off processing. Sapphire is an anisotropic material with the dielectric constants $\varepsilon_{\parallel} = 11.6$ and $\varepsilon_{\perp} = 9.4$ [122]. Because the IE3D software package cannot account for anisotropic dielectrics, the dielectric constant of sapphire was set to the average value of 10.5 during the simulation as an approximation. The dielectric constants were set to 9.7 for GaN and 9.5 for AlGaN respectively, and gold was selected for the metallization.

For a complete transmission line sensor, there are three distinct regions. The first is the free-standing membrane CPW with suspended ground conductor for the thermopile power sensor function. The second is the input/output transmission lines with a standard CPW structure for connection with the external circuit. To connect these two regions, a third, tapered section is required.

The layout of the substrate structure of the input and output CPW lines is the same as shown in Figure 6.7(a). The best values found for the input and output line dimensions are a center conductor width of $w = 68$ µm, and a slot width of $s = 15$ µm. The real part of the characteristic impedance of the transmission line varies in the range of 48-52 Ω over the frequency range from 1 GHz to 40 GHz, and the imaginary part is less than 2 Ω. A typical simulation result is shown in Figure 6.8(a). As can be seen, $S_{11}$ for this line geometry on a Smith chart forms a small circle and is close to the origin. The length of the test line for this calculation is 10 mm. The return loss of
a typical length of line with these dimensions was also simulated. Fig. 6.8(b) shows the simulated S-parameters for a 150 µm long CPW with these dimensions, showing excellent return loss (< -30 dB) and very low insertion loss (< 0.5 dB).

Fig. 6.8 (a) Smith chart for a 10 mm long standard CPW; (b) S parameter values for 150 µm long standard CPW.
Simulations have also been performed to design the suspended membrane portion of the sensor. A typical result is shown in Figure 6.9. For this simulation, the width of the center conductor is 30 µm, and the horizontal distance between the center conductor and the ground metallization is 20 µm. These dimensions are selected because they result in a characteristic impedance of nearly 50 Ω, in order to match the standard CPW section. A membrane length of 400 µm was selected as a compromise between obtaining high sensor responsivity (longer membrane) and concern that an excessively long ground conductor air bridge would be too fragile. Dimensions on this scale have been previously demonstrated for GaAs/AlGaAs-based devices of this type [111, 112]. As shown in Fig. 6.9, the return loss of the suspended CPW is better than 25 dB to 35 GHz, with modest but noticeable loss (which is needed to create the sensor action.)

Fig. 6.9 Magnitude of S parameters for a membrane CPW with suspended ground conductors; the length of CPW is 400 µm.
These sections can be connected with a short tapered section to transition from the standard CPW configuration to the suspended membrane CPW. As the length of this section can be made short, its effect on device performance is expected to be minimal.

6.5 Summary of the power sensor design

As described above, the thermopiles lie on a suspended membrane. One concern with this arrangement is whether the thermopiles will interfere with the electromagnetic operation of the membrane CPW. Figure 6.10 shows the simulated electric field distribution using the Quickfield software package from Tera Analysis Ltd. [123]. As can be seen, the electric field distribution is primarily concentrated in the CPW slots. Thus, in order to minimize any interference between the thermopiles and the electromagnetic waves on the CPW, the hot junctions of the thermopiles should be placed under the edge of the suspended ground conductors. The Quickfield software package has also been used to simulate the thermal flow field as shown in Figure 6.11. A summary of the sizes of the studied CPW structure obtained is listed in Figure 6.12 and Table 6.1.
Fig. 6.10 Electrical field simulation result of suspended ground conductor CPW.

Fig. 6.11 Thermal field simulation result of thermopiles and membrane.
Fig. 6.12 Cross-sectional schematic illustration of the suspended membrane CPW with probe pads; because of symmetry, only a quarter of the whole structure is shown.

TABLE 6.1 DESCRIPTION OF THE STUDIED CPW

| Description          | \( L_1 \) (µm) | \( s/w/g \) (µm) | \( |Z| \) characteristic impedance (Ω) |
|----------------------|----------------|-----------------|-------------------------------------|
| Input/Output CPW     | 150            | 16/68/100       | 50                                  |
| Taper                | 50             | Linear taper    | 50                                  |
| Membrane CPW         | 400            | 20/30/115       | 50                                  |
The thermal conductivity is 1.3 W/cm-K at 300 K for wurtzite GaN, and 2.85~3.19 W/cm-K for AlN [19]. Due to limited available data on the thermal properties of AlGaN, a linearly interpolate model is used as an approximation. According to reference [124], the specific heats of both GaN and AlN fall into the range 29.83~35.48 J/mol-K at room temperature. The mass densities for GaN and AlN are 6.15 g/cm³ and 3.23 g/cm³, respectively [125], and the corresponding molar masses are 83.73 g/mole and 41 g/mole, respectively.

Combining the sensor’s dimensions obtained from CPW calculations with the material properties for the GaN/AlGaN material system, the responsivity, thermal time constant, and noise equivalent power can be estimated theoretically. For example, the length of the thermopiles (lth) is 115 µm according to the value of g for the membrane CPW in Table 6.1, and a 200 nm thick GaN layer on a 1 µm AlGaN membrane was chosen for the thermopiles. For this analysis, we assume the number of thermopiles on each side of the CPW is N and the width of a thermopile is w µm, so Ntotal = 2N. Because of the symmetry on both sides, it can be assumed that a half of heat produced by ohmic loss passes into each side of center conductor, and the thermopiles under one ground plane are considered at first. The thermal resistance for the region under each ground plane can be expressed as (according to Fig. 6.1):

\[
R_{th,one side} = R_{th,slot} + \left[ R_{th,AlGaN} \left( \frac{R_{th,GaN}}{N} \right) \right]
\]

(Eq. 6.22)
where $R_{th,\text{slot}}$ is the thermal resistance corresponding to the AlGaN membrane between the center and the ground conductors, $R_{th,\text{AlGaN}}$ is for the AlGaN membrane under the ground, and $R_{th,\text{GaN}}$ is for the GaN thermopiles on top of the AlGaN membrane and beneath the ground plate.

With the dimension data in Table 6.1, Eq. 6.10, and the thermal conductivity of GaN ($K_{\text{GaN}}$) and AlGaN ($K_{\text{AlGaN}}$), the thermal resistance including the regions under both ground plates is expressed as:

$$R_{th} = \frac{1}{2} \left( \frac{W_s}{K_{\text{AlGaN}} L_{\text{mem}} t_{\text{AlGaN}}} + \left[ \frac{l_{th}}{K_{\text{AlGaN}} L_{\text{mem}} t_{\text{AlGaN}}} \parallel \frac{1}{N} \frac{l_{th}}{K_{\text{GaN}} w t_{\text{GaN}}} \right] \right) \quad \text{(Eq. 6.23)}$$

where $W_s$ is the width of the slot between the center and ground conductors, $N$ is the number of thermopiles under one ground plate, $w$ and $l_{th}$ are the width and the length of a thermopile, $L_{\text{mem}}$ is the length of the membrane CPW, $t_{\text{AlGaN}}$ and $t_{\text{GaN}}$ are the thickness of the AlGaN and GaN, respectively.

The thermal resistance should be large for good responsivity performance. With the thermal conductivity of 2 W/cm-K for AlGaN and 1.3 W/cm-K for GaN and the dimensions from Table 6.1, the thermal resistance $R_{th,\text{slot}} = 1437 \ \Omega$, and $R_{th,\text{AlGaN}} = 250 \ \Omega$ (see Eq. 6.22). Since the resistance of the thermopiles should not decrease the total resistance too much, let $\frac{R_{th,\text{GaN}}}{N} \geq 10 R_{th,\text{AlGaN}}$, which leads to $n w \leq 302$. Under these conditions, Eq. 6.23 can be simplified as:
The electrical resistance of the designed sensor can be calculated in the same way. The AlGaN layer is unintentionally doped, and it has been reported that the resistivity of unintentionally doped AlGaN increases so rapidly with increasing AlN fraction so that the AlGaN is essentially insulating for AlN molar fractions \( \geq 20\% \) [19]. Consequently, only the electrical resistance of the n-doped GaN thermopiles is considered. The conductivity of n-doped GaN on insulating AlGaN can be easily measured with TLM techniques as discussed in Chapter 2. For bulk GaN with \( n \sim 10^{17} \text{ cm}^{-3} \), the conductivity is about \( 6 \sim 12 \Omega^{-1}\text{-cm}^{-1} \) [125], and the electrical resistance can be expressed as:

\[
R_e = 2N \times \frac{l_{th}}{\sigma w t_{\text{GaN}}} \tag{Eq. 6.25}
\]

where \( \sigma = 9 \Omega^{-1}\text{-cm}^{-1} \) has been taken as a representative value, and the thermopiles on both sides of the CPW structure are connected in series.

The thermal capacitance of the designed sensor can also be calculated. Since the specific heats of both GaN and AlN fall into the range 29.83–35.48 J/mol-K at
room temperature, a value of 32 J/mol-K can be used for approximation for both GaN and AlGaN. The thermal capacitance can be expressed as:

\[
C_{th} = 2 \left[ C_{sp, AlGaN} L_{mem \text{AlGaN}} (l_{th} + W_s) m_{AlGaN} + NC_{sp, GaN} l_{th} w t_{AlGaN} m_{GaN} \right] \quad \text{(Eq. 6.26)}
\]

where \(m_{AlGaN}\) ranges from \(7.35 \times 10^{-14} (m_{GaN})\) to \(7.87 \times 10^{-14}\) mole/\(\mu m^3\) with AlN molar fraction of 0 to 100%, and \(C_{sp, AlGaN}\) and \(C_{sp, GaN}\) are the specific heats of AlGaN and GaN, respectively.

With the above calculated results, the responsivity, thermal time constant and noise equivalent power can be estimated as:

\[
R_S = \alpha 2NSR_{th} \approx \alpha NS \left[ \frac{W_s}{K_{AlGaN} L_{mem \text{AlGaN}}} + \frac{l_{th}}{K_{AlGaN} L_{mem \text{AlGaN}}} \right] \quad \text{(Eq. 6.26)}
\]

\[
\tau = C_{th} R_{th} \approx \left[ C_{sp, AlGaN} L_{mem \text{AlGaN}} (l_{th} + W_s) m_{AlGaN} + NC_{sp, GaN} l_{th} w t_{AlGaN} m_{GaN} \right] 
\times \left[ \frac{W_s}{K_{AlGaN} L_{mem \text{AlGaN}}} + \frac{l_{th}}{K_{AlGaN} L_{mem \text{AlGaN}}} \right] \quad \text{(Eq. 6.27)}
\]

\[
NEP = \frac{1}{R_s} \sqrt{4k_B R S T \Delta f} \\
= \alpha S \sqrt{\frac{8k_B T \Delta f \times l_{th}}{\sigma_{GaN}}} \sqrt{\frac{1}{NW}} \quad \text{(Eq. 6.28)}
\]
For good performance, responsivity should be high and the thermal time constant should be low. From Equations 6.26 and 6.27, there is a trade-off between $R_s$ and $\tau$. The value of $\frac{\tau}{R_s}$ can be used for analysis to find the optimized value, as shown in Eq. 6.29.

$$\frac{\tau}{R_s} = \frac{C_{sp,AlGaN}^L L_{mem,AlGaN} (l_{th} + W_s) m_{AlGaN}}{\alpha S} \cdot \frac{1}{N} + \frac{C_{sp,GaN}^L l_{th,AlGaN} m_{GaN}}{\alpha S} \cdot w$$  \hspace{1cm} (Eq. 6.29)

In equation 6.29, $N$ should be large and $W$ should be small for a minimum $\frac{\tau}{R_s}$.

Both the minimum space between adjacent thermopiles and the minimum thermopile width are 2 $\mu$m, based on processing considerations. In addition, the maximal number of thermopiles under one ground plate is limited by the length of membrane CPW, following the condition below:

$$N_{\text{max}} \times w + (N_{\text{max}} + 1) \times 2\mu m \leq 400\mu m$$

and so, for the minimum width of the thermopile (2 $\mu$m), the $N_{\text{max}}$ is 99.

For this optimized sensor layout, the total number of thermopiles is 198 under both ground plates, the width of the thermopile is 2 $\mu$m, and the space between adjacent thermopiles is also 2 $\mu$m. For these simulations, AlGaN with thermal conductivity of 2 W/cm-K and GaN with thermal conductivity of 1.3 W/cm-K are
used, and absorption coefficient $\alpha$ in Equation 6.26 is $1 - |S_{21}|^2 \approx 5.6\%$, where $S_{21}$ is 0.25 dB (the average value from Fig. 6.9). The layout and performance are summarized in Table 6.2.

<table>
<thead>
<tr>
<th><strong>Parameter</strong></th>
<th><strong>Value</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermopile length</td>
<td>115 µm</td>
</tr>
<tr>
<td>Thermopile width</td>
<td>2 µm</td>
</tr>
<tr>
<td>Thermopile thickness</td>
<td>2 µm</td>
</tr>
<tr>
<td>Thermopile number</td>
<td>198</td>
</tr>
<tr>
<td>Responsivity ($R_s$)</td>
<td>3.61 V/W</td>
</tr>
<tr>
<td>Thermal constant time ($\tau$)</td>
<td>$2.32 \times 10^{-4}$ s</td>
</tr>
<tr>
<td>Noise equivalent power (NEP)</td>
<td>$2.84 \times 10^{-7}$ W/√Hz</td>
</tr>
<tr>
<td>Detectable minimum signal</td>
<td>$7.44 \times 10^{-6}$ W</td>
</tr>
</tbody>
</table>

In the above calculation, only the thermal loss in semiconductor membrane/thermopile is taken into account, although in general the thermal resistance of the designed sensor should account for heat losses through atmosphere, radiation and sensor membrane material. However, as discussed in Section 6.3, the sensor can be fine tuned following the same methodology, with the measured data which can be extracted from the first fabricated device. In any case, this level of performance is well suited for power monitoring in system.
CHAPTER VII
SUMMARY AND CONCLUSIONS

Micromachining techniques for GaN and related materials based on photoelectrochemical (PEC) etching have been developed and demonstrated. Although excellent results using advanced dry-etching have been obtained by other researchers for GaN and related materials, a viable PEC etching process is still attractive since PEC etching is expected to result in less process-induced damage. In addition, PEC etching offers a number of unique characteristics, including dopant-selective etching and wavelength-selective etching. These advantages and features are expected to permit high-performance electronic and optoelectronic devices to be realized in a flexible and robust fabrication process. In this thesis, the PEC etching of GaN and related materials has been demonstrated, the mechanism of PEC etching of GaN has been investigated, and a model for PEC etching of this material system has been developed. Methods for the controlling the smoothness of the etched surface, as well as the use of backside-illuminated PEC etching, front-side illuminated PEC etching enhanced with applied voltage bias, and wavelength-selective PEC etching for the fabrication of suspended membrane structures have also been investigated.

The physical mechanisms governing PEC etching of GaN have been studied, and a two-step model that is consistent with experimental observations has been proposed. This model is consistent with known chemical reactions, and also is
consistent with the observed time dependence of the etching current. The presence of a gallium oxide layer formed during PEC etching at the sample-electrolyte interface that mediates etching has been verified with XPS. The etch rate and etched surface morphology have been found to be directly related to the etching conditions. Key process parameters include illumination light intensity, electrolyte concentration, and voltage bias. The etch rate increases with increasing electrolyte concentration and with increasing incident optical intensity. Electrolyte solutions at elevated temperatures were also found to increase the etch rate.

PEC-etched surfaces often exhibit a rough morphology, which has been found to be correlated to the high density of dislocations in GaN. These rough surfaces are not well suited for many device applications. The study of PEC process conditions has shown that etching in low concentration electrolyte solutions with high light intensity improves the etched surface’s smoothness, but at the expense of a low etch rate. It has been found that an applied voltage bias during etching can also improve the etched surface morphology, as well as increase the etch rate. Use of a suitable voltage bias has been demonstrated to produce a very smooth surface, with root-mean-square surface roughness of approximately 0.5 nm. This surface roughness is comparable to that of unetched as-grown GaN surfaces (0.4 nm rms).

The development of lateral photoelectrochemical etching of GaN for the fabrication of deeply undercut structures has also been demonstrated. Conventional front-side illuminated PEC etching without voltage bias applied was found not to etch the GaN in regions masked by Ti, and thus is not suitable for fabricating undercut
structures. Through-wafer backside-illuminated PEC etching was evaluated for fabricating undercut structures. However, the etched results were found to be non-uniform, and an “inverted pyramid” GaN morphology was observed. Use of an applied voltage bias was found to enhance the lateral PEC etching of GaN in front-side illuminated PEC etching. With sufficient etch time, suspended Ti cantilevers were fully released after uniformly and completely removing the GaN from under the cantilevers. This is the first reported observation of this effect; a simple explanation for this effect has been proposed.

The formation of dielectric and semiconductor membranes on GaN using the PEC etching technique has also been investigated. Released dielectric SiO₂ membranes on GaN were fabricated and demonstrated using PEC etching. Transparent dielectrics such as SiO₂ allow the UV light to generate electron-hole pairs in the GaN underneath the SiO₂, leading to selective PEC undercut etching of the GaN. Fabrication of AlGaN semiconductor membranes has also been demonstrated, using bandgap-selective PEC etching with a filtered light source. This technique allows selective etching of GaN without etching the wide bandgap AlGaN. These processes are promising for fabrication of sensors and other MEMS devices that require free-standing membranes.

An inline transmissive microwave power sensor, enabled by the ability to micromachine GaN and related materials demonstrated here, has been designed and simulated. It may offer several advantages over conventional power sensors by allowing it to be easily integrated with low-loss coplanar transmission lines and GaN-
based transistors. Fundamental simulation-based studies of the thermal and electromagnetic properties of the sensor have been performed, and the relationship between the sensor’s structure and performance has been established, illustrating a potential application of the developed fabrication processes.
APPENDIX A

THE SPECTRAL IRRADIANCE OF LIGHT SOURCES

Fig. A. 1 Spectral irradiance of various Arc lamps; 6292 in (a) is the 200 W light source, and 6295 in (b) is the 1000 W light source used in this work during PEC etching.[126]
APPENDIX B

C PROGRAM TO ACQUIRE DATA FROM SOURCEMETER

/* Basic Communication */
/*version 1.0 ---ported to Sun with NI GPIB488.2, converted for Sourcemeter 2400*/

#include <stdlib.h>
#include <sys/ugpib.h>
#include <stdio.h>
#include <fcntl.h>
#include <math.h>
#include <termios.h>
#include <string.h>
#define sample 2400
    /*the number of the sampling points; 1000 points=7 minutes*/
    /*sampling step is 0.5 seconds*/
    /* if sampling time is 5 minutes, the number is 1200; */
    /* if sampling time is 10 minutes, the number is 2400; */
    /* if sampling time is 15 minutes, the number is 3600; */

void main()
{
    FILE *fo;       /* output file pointer */
    char fn[80], power[80], conc[80], direct[80]; /* output filename */
    int Smeter;    /* file descriptor for digital multimeter */
    int i,j;       /* loop control variable */
    double VOLT[sample], CURR[sample], RESS[sample], TIME[sample], timebuffer; /* stores measurement readings from Sourcemeter */
    char   as[80];  /* store the return value */
    char *tokenpt; /*pointer to break down the long string*/

    /* output file processing*/
    printf ("Enter front or back for front etching or back etching
");
scanf("%s", direct);
printf("Enter power intensity mW/cm² for saving this info: \n");
scanf("%s", power);
printf("Enter concentration of solution M for saving this info: \n");
scanf("%s", conc);
printf("Enter file for saving this info: (type ` to not save)\n");
scanf("%s", fn);

if ((Smeter = ibdev(0, 11, 0, 10, 1, 0)) < 0)
    report_error(Smeter, "Could not open Sourcemeter");

/* clearing the device */

ibclr(Smeter);
if (ibsta & ERR)
    report_error(Smeter, "Could not initialize Sourcemeter");
ibwrt(Smeter, "*RST", 4); /*restore GPIB default conditions*/
ibwrt(Smeter, ":SENS:FUNC:CONC OFF", 20); /*turn off concurrent functions*/
/*ibwrt(Smeter, ":SENS:FUNC:ON:ALL", 17); */
ibwrt(Smeter, ":SOUR:FUNC VOLT", 15); /*select V-source mode*/
ibwrt(Smeter, ":SENS:CURR:DC:PROT 0.01", 23); /*set current compliance*/
ibwrt(Smeter, ":SENS:FUNC:ON 'CURR:DC'", 23); /*specify Amps measurement function */
ibwrt(Smeter, ":SENS:CURR:DC:RANG:AUTO ON", 27);
ibwrt(Smeter, ":SOUR:VOLT:MODE FIX", 19); /*select fixed DC sourcing mode for V-source*/
ibwrt(Smeter, ":SOUR:VOLT DEF", 14); /*set amplitude for fixed V-source to zero*/
/*ibwrt(Smeter, ":SENS:CURR:DC:RANG 0.001", 24);*/
ibwrt(Smeter, ":OUTPUT ON", 10); /*turn on source output*/
    for (i=0; i < sample; i++) /* Take sample readings */
    {
        usleep(250000);
        /*ibwrt(Smeter, ":MEAS:CURR:DC?", 14);*/
        ibwrt(Smeter, ":MEAS?", 6);
    }
ibwrt(Smeter, "FORMat:ELements VOLTage, CURRent, TIME", 37);
ibwrt(Smeter, "SEND[1]:FUNCTION:ON:ALL", 25);
buffer[70]=getpt(Smeter);
if (ibsta & ERR)
  report_error(Smeter, "Could not trigger Sourcemeter");
/* Reading data from Sourcemeter */
ibrd(Smeter, as, 80*sizeof(char));
if (ibsta & ERR)
  report_error(Smeter, "Could not read data from Sourcemeter");

printf("sample point i= %d\n\r", i);
printf("string returned %s; its length %d\n\r", as, strlen(as));

tokenpt=strtok(as,"",");
VOLT[i]=atof(tokenpt);
printf("voltage=%e", VOLT[i]);
if (tokenpt!=NULL)
  { tokenpt=strtok(NULL,"",");
    CURR[i]=atof(tokenpt);
    printf("current=%e", CURR[i]);
  }
if (tokenpt!=NULL)
  { tokenpt=strtok(NULL,"",");
    RESS[i]=atof(tokenpt);
    printf("resistance=%e", RESS[i]);
  }
if (tokenpt!=NULL)
  { tokenpt=strtok(NULL,"",");
    TIME[i]=atof(tokenpt);
    if (i==0) {timebuffer=TIME[i];}
    TIME[i]=TIME[i]-timebuffer;
    printf("time=%e\n\r", TIME[i]);
  }

ibonl(Smeter, 0);  /* Take Sourcemeter off-line */

/* output file processing*/
if (fn[0]!=""")
{
    fo = fopen(fn,"w");
    fprintf(fo,"raw Sourcemeter measurement data\n\n");
    fprintf(fo,"The direction of illumination light:\n");
    fprintf(fo,"\t%s \n\n",direct);
    fprintf(fo,"power intensity:\n");
    fprintf(fo,"\t%s mW/cm2 \n\n",power);
    fprintf(fo,"concentration of solution:\n");
    fprintf(fo,"\t%s \n\n",conc);
    fprintf(fo,"\tTime\t\tVoltage\t\tCurrent\t\n");
    for (j=0; j<sample; j++)
    { fprintf(fo,"\t%e\t",TIME[j]);
      fprintf(fo,"\t%e\t",VOLT[j]);
      fprintf(fo,"\t%e\t",CURR[j]);
      fprintf(fo,"\n");
    }
    fclose (fo);
}

report_error(int fd, char *errmsg)
{
    fprintf(stderr, "Error %d: %s\n", iberr, errmsg);
    if (fd != -1)
    { 
        printf("Cleanup: taking board off-line\n");
        ibonl(fd,0);
    }
    exit(1);              /* abort program */
}
REFERENCES


150


121. Guide to using IE3D, Zeland Inc.

123. Guide to use Quickfield, Quickfield Inc.


126. The Book of Photon Tools, Oriel Inc.