Comparison of Different GaN Etching Techniques

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Abstract

Several Gallium Nitride etching techniques are reviewed and compared. The GaN binary etching technique is selected and used for this experiment, the GaN profile after etching is measured with Dektak profilometer and AFM. Three types of GaN films such as intrinsic GaN, n-type GaN and p-type GaN have been used in the binary etching technique. The experiment results show that binary etching can be utilized for GaN wet etching with good control and precision at room temperature, and at higher temperatures, too.

INTRODUCTION

GaN as a wide band gap III-V compound semiconductor has been recently studied intensively. High performance GaN HFET and MOSFET have been both demonstrated [1] [2]. The GaN processing techniques is crucial in order to achieve good performance of GaN based devices. Many GaN etching methods have been tried. The most of GaN etch are done by plasma etching which has disadvantages such as easy to generate ion-induce damages and difficult to obtain smooth etched sidewall [3][4]. Several wet GaN etch techniques have been tried including photo-enhanced electrochemical (PEC) wet etch [5][6][7], photo-assisted cryogenic etch (PAC) [8], Crystallographic wet etch [9], photo-assisted anodic etch [10], Wet chemical digital etch of GaAs at room temperature [11], and PEC binary etch using $K_2S_2O_8$ and KOH [12]. In this study, the PEC binary GaN etching technique using potassium persulphate $K_2S_2O_8$ and potassium hydroxide KOH is selected among the above GaN web etching techniques. Instead of using an ultraviolet (UV) light source, we try not to use any special light sources. For better surface roughness control, we employed a technique named digital etch. The experimental details and the experimental results will be shown in the later sections of this paper.

GAN ETCHING TECHNIQUES REVIEW AND EXPERIMENTAL RESULTS

Several etching techniques have been reviewed and the etch rate and surface roughness are summarized in Fig.1, Fig.2 and Table 1.

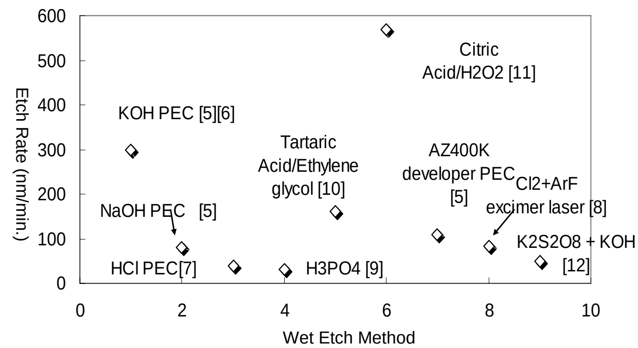


Figure 1.Etch rate of several etching techniques.

The Above figure shows several of the published data of GaN wet etch rate. As can be seen the GaN wet etch usually requires an oxidization agent and a reduction agent. The Citric Acid/H_2O_2 wet etch [11] shows the highest etch rate about 580 nm per minute, while other etch techniques such as KOH PEC [5][6], and Tartaric Acid/Ethylene glycol etch [10] also show promising etch rate.

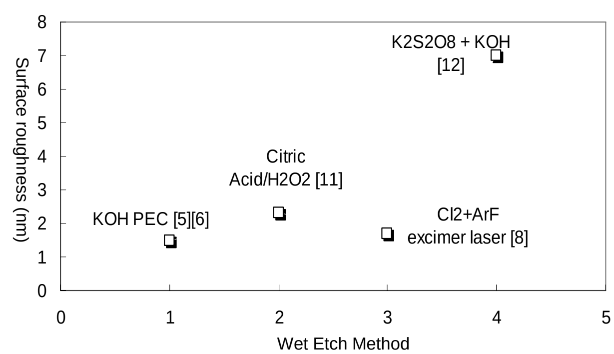


Figure 2.GaN surface roughness after etch using several etching techniques.

However besides etch rate, the surface roughness is crucial to GaN based device processing. The above Fig. 2 shows the published data of GaN surface roughness after wet etch. The Potassium Hydroxide (KOH) PEC etch and Cl_2 with ArF excimer laser etch show promising GaN surface roughness after etching. The Potassium persulfate/Potassium Hydroxide ($K_2S_2O_8$/KOH) etching method [12] shows a good surface rougness too.

TABLE I
REVIEW OF DIFFERENT GAN ETCHING TECHNIQUES

No.	Electrolyte used	Method	Etch Rate (nm/min)	Roughness
1	KOH	PEC[5][6]	50 for 0.02M >300 for 0.04M	1.5nm
2	NaOH	PEC[5]	80	NA
3	HCl	PEC[7]	1.5-40	NA
4	H_3PO_4	Crystallographic wet etch[9]	13-32	NA
5	Tartaric Acid/Ethylene Glycol	Photo-assisted Anodic etching[10]	160	81.5nm
6	Citric Acid/H_2O_2 (2:1)	Oxidation/Reduction[11]	570	2.3nm
7	AZ400K developer	PEC[5]	110	NA
8	Cl_2+ArF excimer Laser (dry etch)	PAC[8]	84 @210K	1.7nm
9	$K_2S_2O_8$ + KOH	PEC[12]	50	7nm

In our experiment, the PEC binary GaN etching method is selected because of the following reasons: 1). Binary etch enables better control and precision as shown in the above Figures and Table.1. 2). It does not require sophisticated equipment. 3) It can be conducted at both room temperature and higher temperature. 4) It does not require any electrode. And 5). External stimulus are not required.

Several GaN samples are grown on C plane sapphire substrate by MOCVD. The thicknesses of two n-GaN films are about 500nm and 700nm respectively. The intrinsic GaN film is about 1um, and the p-GaN film is about 1um. The aluminum nitride (AlN) buffer layer is used between GaN and sapphire. The Si is used as n type dopant, the n-GaN doping concentration is 5×10^{18} cm^{-3} and 1×10^{18} cm^{-3}, respectively. The p-GaN is doped with Mg and the doping concentration is about 1×10^{16} $cm^{-}3$.

All of the GaN films have been patterned with a LED mask, then 200 nm Ni layer has been deposited on the GaN films using E-beam deposition, after Ni lift-off, the patterned GaN films left with Ni and GaN films.

The $K_2S_2O_8$ acts as an oxidizing agent and KOH acts as a reducing agent. The relevant reactions in the GaN binary etch might be the following according to Bardwell et al [12], but in our experiment we do not use the ultraviolet light:

$$GaN + photon \rightarrow GaN + e^- + p^+$$

$$GaN + 3p^+ \rightarrow Ga^{3+} + \frac{1}{2}N_2$$

$$S_2O_8{}^{2-} + 2e^- \rightarrow SO_4{}^{2-}$$

$$S_2O_8{}^{2-} + photon \rightarrow 2SO_4{}^{-*}$$

$$SO_4{}^{-*} + OH^- \rightarrow SO_4{}^{2-} + OH^*$$

$$SO_4{}^{-*} + e^- \rightarrow SO_4{}^{2-}$$

$$OH^- + e^- \rightarrow OH^-$$

$$O_2 + OH^- \rightarrow O_3{}^- + H^+$$

The etching process is carried out in the following cycles: 1) Soak in 5% $K_2S_2O_8$ solution for 30 seconds; 2) wash in DI water for 30 seconds; 3) Soak in 10% KOH for 30 seconds; 4) wash in DI water for 30 seconds; 5) repeat above steps for 50 cycles. 6) Blow dry with Nitrogen. Following the above procedure, we have tried the $K_2S_2O_8$/KOH binary etch on intrinsic GaN, n-GaN and p-GaN films at room temperature, 50°C, and 75°C.

The Dektak 3030 profilometer is used to measure the GaN surface profile before and after the binary etch. The patterned Ni to GaN step height difference before and after binary etch is the GaN etched away.

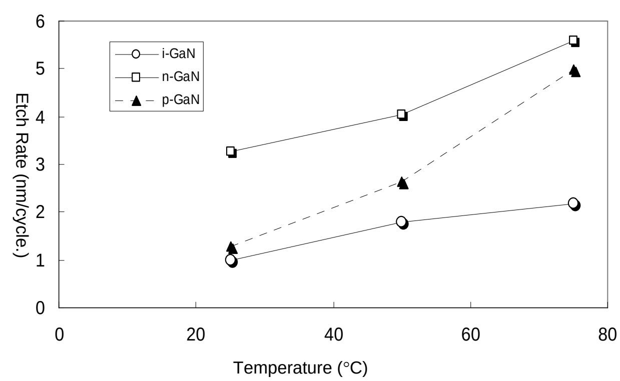


Figure 3.GaN $K_2S_2O_8$/KOH binary etch rate vs. temperature.

The above Fig. 3 shows the intrinsic GaN, n-GaN and p-GaN films etch rate (in nm/cycle) versus temperature from room temperature 25°C up to 75°C. Note 1 cycle takes about total 2minutes (30 seconds' of 5% $K_2S_2O_8$, 30 seconds' of KOH and 60 seconds of DI water). The etch rate is not as high as in [12] because of two reasons. First, we didn't use Ultraviolet light source which can obviously increase the chemical reaction rate. Second, we did in the "Digital" way of wet etch, so basically we intentionally reduce the GaN etch rate in order to achieve better surface roughness control.

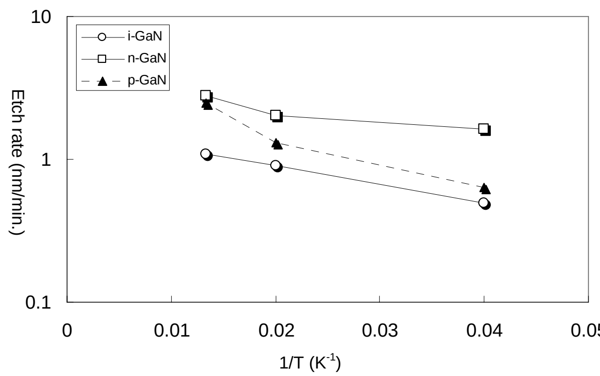
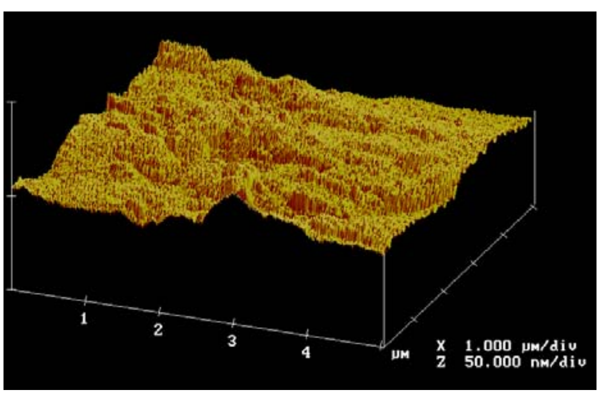


Figure 4.GaN $K_2S_2O_8$/KOH binary etch rate Arrhenius law.

The above Fig. 4 plotted the etch rate achieved in nm per minute versus one over temperature. The etch rate is plotted as log scale, the linearity of the etch rate curves show that the GaN wet etch rate versus temperature also follows Arrhenius law relation. The GaN wet etch rate is around 1nm/min. and increase to around 2nm/min. at 75°C. And the n-GaN has highest etch rate, the possible reason might be higher doping concentration and more defects which make it easier for initial etching to start.

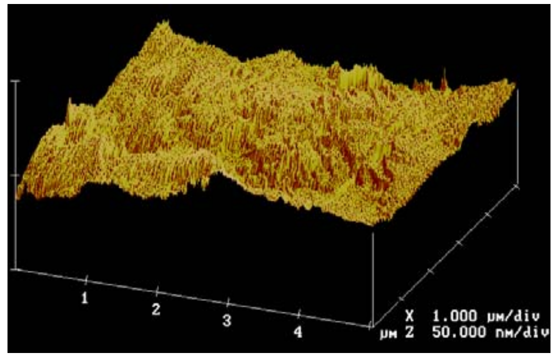
Besides Dektak profile measurement, we also used AFM for surface topology and roughness measurement. The AFM image of GaN surface before and after GaN binary etch are shown in the following two figures.



n-GaN surface roughness 3.8nm before etch

Figure 5.n-GaN surface RMS roughness before etch measured by AFM

The above AFM image is taken by a contact mode AFM scan, the X and Y directions are the scan area, the Z direction shows the surface roughness. The AFM image shows that the GaN surface is smooth before GaN etch which justified our MOCVD growth techniques.



n-GaN surface roughness 4.9nm after etch

Figure 6.n-GaN surface RMS roughness after etch measured by AFM

The above Fig. 6 shows the n-GaN film surface roughness after GaN etch. The surface rougness are calculated by RMS.

More AFM data are necessary to fully analyze the surface rougness for the several different GaN films and for the binary etching at different temperatures. Unfortunately these AFM data are not available due to our current AFM break down.

CONCLUSIONS

The $K_2S_2O_8$/KOH binary etch is successfully performed on intrinsic GaN, n doped GaN and p doped GaN films on sapphire at room temperature and elevated temperature, respectively. The etch rate-temperature relationship agree with Arrhenius law. The etch rate is relatively low but it can control the surface roughness with high precision. The in-depth study is needed for the binary etch, but the room temperature experimental results shown in this study demonstrated very promising results of GaN surface roughness control.

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REFERENCES

[1] V. Kumar et al., "AlGaN/GaN HEMTs on SiC with f_T of over 120GHz". IEEE Electron Device Lett., vol.23, No. 5, pp455-457 May 2002.

[2] Matocha. K, Chow. T.P, Gutmann. R.J. "High-voltage normally off GaN MOSFETs on sapphire substrates". IEEE Transaction on Electron Devices. vol. 52, Issue 1. pp. 6-10, Jan 2005.

[3] S. Nakamura, et al., "InGaN-Based Multi-Quantum-Well-Structure Laser Diodes". Jpn. J. Appl. Phys., Part 2 35, L74, 1996.

[4] F. Binet, et al., "Realization and optical characterization of etched mirror facets in GaN cavities". Appl. Phys. Lett. 72, pp960, 1998.

[5] Cho. H, Donovan. S.M., et al., "Photo-electrochemical etching of $In_xGa_{1-x}N$" J. Nitride semiconductor research, 4S1, G6.40, 1999..
[6] Youtsey. C, Adesida. I, and Bulman. G. "Highly anisotropic photo enhanced wet etching of n-type GaN". Appl. Phys. Lett. 71(15), 1997.
[7] Minsky. M.S, White. M, Hiu. E.L."Room-temperature photoenhanced wet etching of GaN". Appl. Phys. Lett. 68(11), 1996.
[8] Hsieh. J.T, Hwang. J.M. and Hwang. H.L."Damage free photo-assisted cryogenic etching of GaN as evidenced by reduction of yellow luminescence". MRS. Internet J. Nitride Semicond. Res. 4S1, G10.6, 1999.
[9] Stocker. D.A, Schubert. E. F and Redwing. J.M. "Crystallographic wet chemical etching of GaN". Appl. Phys. Lett. 71(15), October 1997.
[10] Lu. H, Wu. Z, and Bhat. I. "Photo-assisted anodic etching of Gallium Nitride". J. Electronchem. Soc. Vol. 144, No. 1, January 1997.
[11] DeSalvo. et al. "Wet chemical digital etching of GaAs at room temperature". J. Electronchem. Soc. Vol. 143, No. 11, November 1996.
[12] Bardwell. et al. "Ultraviolet photo-enhanced wet etching of GaN in $K_2S_2O_8$ solution". J. of Applied Physics, Vol. 89 (7), April 2001.

ACRONYMS

GaN: Gallium Nitride
HFET: Heterojunction Field Effect Transistor
MOSFET: Metal Oxide Semiconductor Field Effect Transistor
MOCVD: MetalOrganic Chemical Vapor Deposition
AFM: Atomic Force Microscopy