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Precision recess of AlGaN/GaN with controllable etching rate using ICP-RIE oxidation and wet etching

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Abstract

A method for highly controllable etching of AlGaN/GaN for the fabrication of high sensitivity HEMT based sensors is developed. The process consists of cyclic oxidation of nitride with O_2 plasma using ICP-RIE etcher followed by wet etching of the oxidized layer. Previously reported cyclic oxidation-based GaN etching obtained very slow etching rate (~0.38 nm/cycle), limited by oxidation depth. The proposed approach allows fine control of the oxidation enabling the formation of accurately controlled recess of very thin (20~30 nm) barrier layers. With optimized power settings, etch rates from ~0.6 to ~11 nm/cycle were obtained. AFM results did not show any increase in surface roughness after etching, indicating that surface quality of the etched layer was not affected by the etching process.

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Keywords: HEMT; gate recess; cyclic etch; AlGaN/GaN; plasma oxidation; ICP-RIE; HEMT-sensor; semiconductor sensor

1. Introduction

Superior electronic, chemical, thermal and mechanical properties of wide bandgap gallium nitride (GaN) have attracted much interest for developing power switching devices [1] and next generation semiconductor sensors [2]. Epitaxial AlGaN/GaN heterojunctions exhibit strong polarization effects, forming high carrier density two

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dimensional electron gas (2DEG) channel at the interface, which results in intrinsically depletion-mode operation. By recess etching of the thin (20~30 nm) AlGaN barrier enhancement-mode operation of AlGaN/GaN high electron mobility transistors (HEMTs) can be achieved [3]. Partial barrier recess has also been applied for Au-free, CMOS compatible ohmic contact resistance reduction [4] and to improve the sensitivity of HEMT-based open-gate NO_2 sensors [5] (Fig. 1).

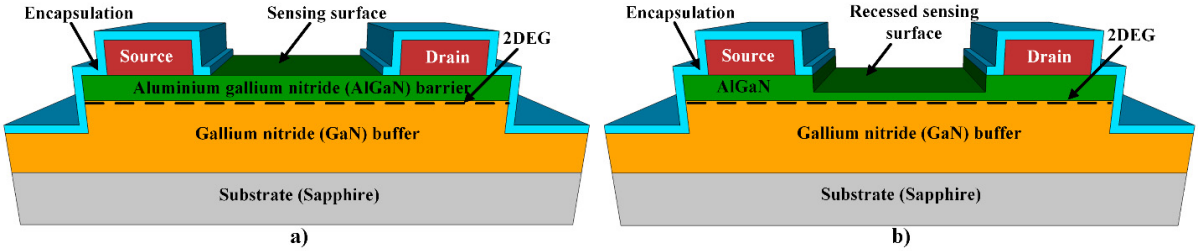


Fig. 1. Schematic representation of non-recessed (a) and recessed (b) open-gate GaN HEMT-based sensor.

AlGaN/GaN recess is commonly done by low power reactive ion etching (RIE) using Cl_2/BCl_3 plasma, which often exhibits difficulties of depth control, non-uniformities, etching residues and lattice damage due to ion bombardment. Increasing the substrate temperature from 20°C to 180°C during inductively coupled plasma (ICP) RIE etching can reduce the amount of Cl-based residues and lower the etched surface roughness [6]. Alternatively, thermal oxidation of AlGaN barrier at 650°C, without oxidizing GaN, coupled with KOH oxide etching at 70°C was successfully demonstrated [7]. Cyclic oxidation of AlGaN, using O_2 plasma asher, followed by wet hydrochloric acid (HCl) etching of the oxidized surface to fabricate recessed-gate GaN MOSFETs was recently reported [8]. Using 300 W RF power for 3 minutes, an etching rate of ~0.38 nm/cycle was obtained, being too slow for most barrier recess applications.

In this report, we present a novel method for precise, low damage cyclic etching of AlGaN/GaN for precision barrier recess applications, using ICP-RIE oxidation and wet etching. Optimization of equipment power settings allowed to obtain a wide range of etching rates ~0.6 to ~11 nm/cycle without any observable increase in surface roughness with respect to the unetched surface.

2. Materials and methods

The HEMT structure used in this work was grown by Suzhou Nanowin Co. on 2 inch sapphire wafers. The heterostructure, starting from the substrate, consisted of 2 μm undoped GaN buffer layer, 1 nm AlN interlayer, 21 nm undoped $Al_{26}Ga_{74}N$ barrier and 1.5 nm GaN cap layer. The wafer surface was cleaned and coated with 300 nm of PECVD SiO_2 used as a hard mask during the etching experiments. The oxide was patterned with photoresist and etched with buffered oxide etchant (BOE), because it does not etch the underlying GaN cap layer. After photoresist removal, the wafers were diced into 7 x 7 mm^2 chips to be used for recess etching experiments. Prior to first oxidation, native oxide was removed by HCl dip. Nitride oxidation was done with ICP-RIE etcher using O_2 plasma for 3 min followed by 1 min oxide etch using 1:4 HCl:H_2O solution at room temperature. Two ICP-RIE systems from different vendors (AST and Oxford Instruments) with different ICP source and RF bias generator power range were used. Oxidation recipe parameters for both systems are summarized in table 1. Only O_2 gas was injected into the chamber during oxidation process. 3 chips were loaded into the etching chamber simultaneously with random orientations for testing each oxidation recipe. After 3 or 4 etching cycles the SiO_2 mask was removed with BOE. Etching depth and surface roughness were measured using Bruker Dimension Edge AFM. Average etch rate per cycle was determined by measuring multiple points across the test samples.

Table 1. Process recipe information for ICP-RIE oxidation.

Parameter	AST Cirie-200	Oxford Plasmalab 100
O_2 flow rate (sccm)	40	40
Pressure (mtorr)	8	8
ICP power (W)	150-450	450
ICP range (W)	0-2000	200-2500
RF power (W)	15-150	75
RF range (W)	0-600	5-400
Oxidation time (s)	180	180

3. Results and discussion

In this work, we have investigated the effects of ICP and RF power on O_2 plasma oxidation of AlGaN/GaN, while other settings were kept constant for all experiments. Average etching rates for the tested RF and ICP power range, using AST system, are shown in Fig. 2. Obtained results showed a linear increase in etching rate with increasing RF power. A wide range of average etching rate from ~0.6 to ~6 nm/cycle was achieved. The dependency on ICP power was less noticeable, with little variation in etching rate, especially for 300 W and 450 W ICP power. The RF generator is used to control the energy of plasma ions while ICP generator is used to optimize plasma density. We conclude that higher energy O_2 ions can penetrate deeper into the nitride layer to form thicker oxide, while the plasma density was not depleted considerably for the tested range, to significantly influence the oxidation process. A 3.4x higher etching rate (11 nm/cycle) was obtained when using Oxford Instruments system in comparison to AST (3.22 nm/cycle) when using same power parameters 450 W/75 W (ICP/RF). These differences could be attributed to numerous equipment design variations e.g. the usable generator power range, chamber size and design, ion energy, etc. Therefore equipment specific optimizations should be carried it out in order to obtain the desired oxidation depth. After 3 cycles etching with the Oxford Instruments tool the measured step height was 33 nm, indicating that the GaN buffer was also etched.

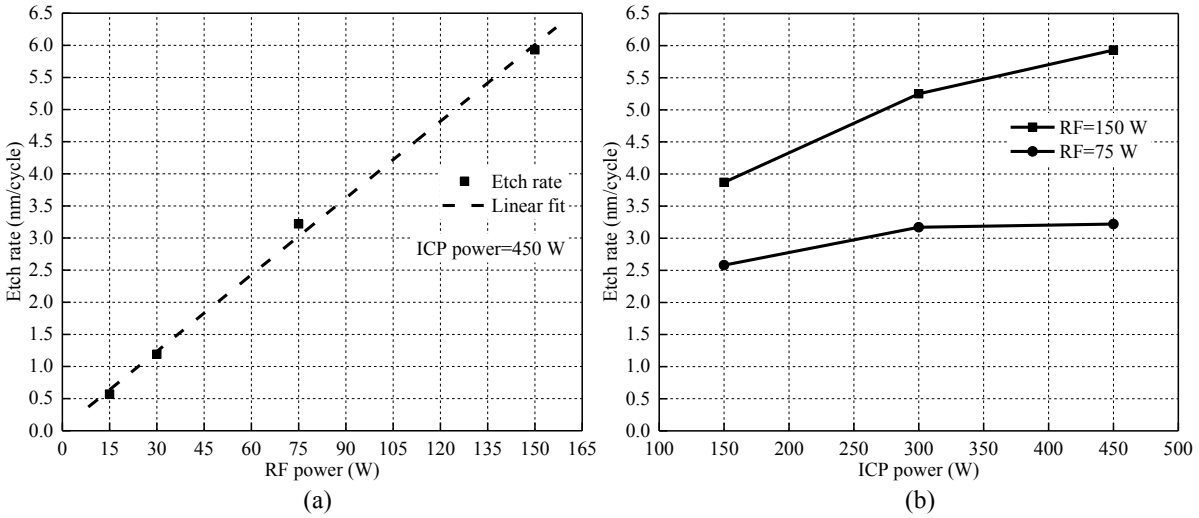
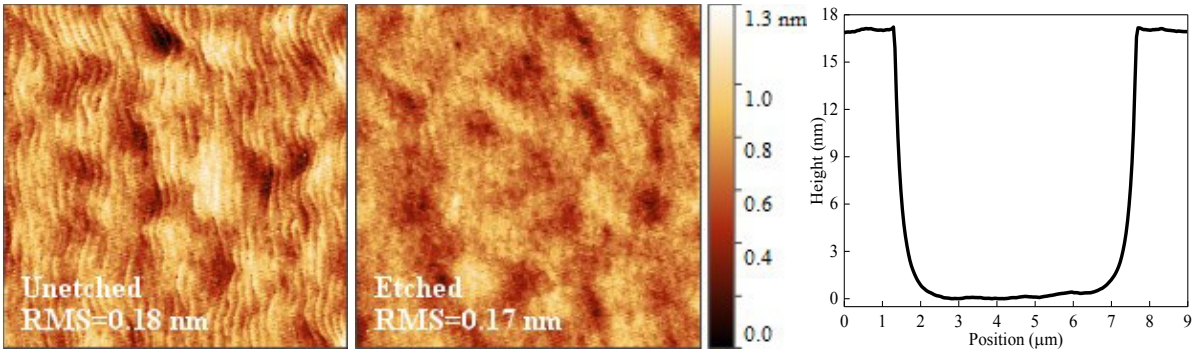


Fig. 2. Etch rate dependency on (a) RF power at constant ICP power and (b) ICP power at constant RF power using AST etcher.

Surface damage after ICP-RIE oxidation based etching was evaluated by roughness measurements. AFM surface morphology images of the unetched (after SiO_2 mask removal with BOE) and etched layers are shown in Fig. 3a-b. After 3 cycles of etching with 450W/150W (ICP/RF) recipe using AST system the RMS roughness remained unchanged. Similarly, roughness was not altered after etching with Oxford Instruments system with unetched and

etched RMS roughness values of 0.22 nm and 0.21 nm respectively. Unlike direct plasma etch, wet etching of the oxidized layer with HCl is highly selective towards the nitride layer and hence no surface damage is induced on the underlying AlGaN/GaN. A step profile across a 6 μm trench (Fig. 3c) shows smooth and uniform bottom surface.



(a) (b) (c)

Fig. 3. AFM surface morphology images of (a) unetched and (b) etched surfaces using AST 450/150 (ICP/RF) recipe and (c) etched profile after 3 oxidation/etching cycles (c).

4. Conclusions

In conclusion, we have demonstrated a precise, low damage cyclic etching of AlGaN/GaN by using ICP-RIE oxidation and wet etching. Controllable etching rates in 0.6~11 nm/cycle range were obtained. This approach is highly promising for the formation of accurate recess of few to several tenths of nm in the thin AlGaN/GaN layers, during HEMT fabrication as well as to improve the sensitivity of GaN HEMT-based chemical sensors, and is suitable for large-volume microfabrication due to reduced number of required cycles. Future work will include the investigations into optimizing the oxidation time to determine the saturated oxidation depth as well as the influence of O_2 gas flow during oxidation. The proposed method will be further applied for fabricating high sensitivity HEMT-based sensors.

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