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Facet formation of a GaN-based device using chemically assisted ion beam etching with a photoresist mask

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The etch characteristics of GaN were investigated using chemically assisted ion beam etching (CAIBE) for Cl_2 as a function of tilt angle. With increasing tilt angle the measured GaN etch rate showed a maximum at 30° similar to the effect of tilt angle on the sputter yield. The etch profiles of GaN etched by tilting the substrate less than 20° showed sidewall trenching. When the tilt angle was more than 30°, an etch tail was observed at the bottom of the etched structure. With the Cl_2 CAIBE, the anisotropy of the GaN etch profile was enhanced as the tilt angle was increased, and a vertical etch profile could be obtained at a 50° tilt angle. The sidewall roughness of the etched GaN laser device varied with the Cl_2 flow rate and ion beam voltage. A highly anisotropic etch profile with a smooth sidewall could be obtained by optimization of the ion beam voltage/current and Cl_2 flow rate. The surface of GaN etched by the Cl_2 CAIBE system showed a Ga-deficient surface due to the removal of Ga by the formation of $GaCl_x$. © *1999 American Vacuum Society.* [S0734-2101(99)14104-6]

I. INTRODUCTION

Gallium nitride has received great interest over the past few years for application in blue/ultraviolet lasers, light emitting diodes, photodetectors, and high temperature and high power electronic devices.[1,2] Currently, GaN facets required for GaN laser devices are fabricated using dry etching due to the difference in the cleavage planes of sapphire substrates and GaN epitaxial layers grown on them. Due to the excellent chemical and thermal stabilities of GaN, wet etching has proven difficult.[3] Dry etching techniques are important for reliable pattern transfer in III nitrides such as GaN due to the resistance of the material to wet chemical etchant. The fabrication of GaN facets using dry etching techniques requires not only high GaN etch rates and high selectivities over mask layers but also a vertical etch profile with a smooth sidewall because the quality of the etched mirrors is often a limiting factor for the performance of the laser.[4] Therefore, the fabrication of vertical high quality facets in III–V semiconductors is one of the key issues when optoelectronic devices are intergrated monolithically.[5] Also, the sidewall smoothness of the laser facets has received attention recently. Some studies report improved methods for minimizing the sidewall roughness during the dry etching.[6] In many instances, striations on the dry etched mesas result from roughness in the initial photoresist mask, and this roughness is transferred to the dielectric mask and then to the GaN. Also, mask erosion during the etching could result in roughness in the case of GaN etching.

Dry etching techniques such as reactive ion etching (RIE), reactive ion beam etching (RIBE), chemically assisted ion beam etching (CAIBE), inductively coupled plasma (ICP) etching, and electron cyclotron resonance (ECR) plasma etching have been investigated in order to obtain vertical and smooth etch profiles. CAIBE is known to be a suitable technique for obtaining vertical profiles with smooth sidewalls for mirror facets.[7–15] There have been a few studies reported on GaN etching using CAIBE, and in them the GaN etching used a 0° tilt angle only and used hard masks such as SiO_2 or Ni/SiO_2 to prevent the loss of mask layers.[10,11] If conventional photoresist can be used as a GaN etch mask, the process steps in making optoelectronic devices can be reduced and the throughput will be increased. Therefore, in this study, the etch characteristics of GaN with conventional photoresist were investigated using Cl_2 CAIBE as a function of tilt angle.

II. EXPERIMENT

GaN samples such as *p*-GaN, *n*-GaN, AlGaN, and InGaN used in the experiment were grown by metalorganic chemical vapor deposition (MOCVD) on sapphire substrates. These GaN samples including device structured GaN(*p*-GaN/AlGaN/InGaN/AlGaN/*n*-GaN) were masked and patterned using a conventional photoresist (Shipley 1400-37). GaN etching was performed using a CAIBE system having a 210-mm-diam ion beam etch source, a Meissner trap, and a load-lock chamber. As the ion beam etch source, a filamentless radio frequency ICP (rf-ICP) ion source with three optically aligned Mo grids was used. A plasma bridge neutralizer used to ignite the rf-ICP source was also used to avoid the positive charge buildup of the substrate and to prevent beam spreading. The current and voltage of the ion beam etch source used in the experiment were fixed at 300 mA and 500 V, respectively. Six sccm of Ar was introduced into the ion source while reactive gases

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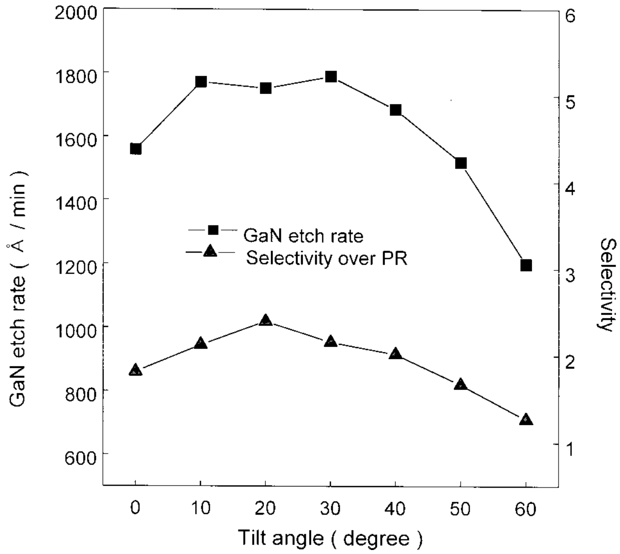

FIG. 1. Angular dependence of the GaN etch rate and the etch selectivity. The angle was measured between the surfaces normal to the substrate and the axis of the ion beam. The Ar ion beam voltage and current were 500 V and 300 mA, respectively, the Cl_2 flow rate was 6 sccm, and the substrate temperature was 20 °C.

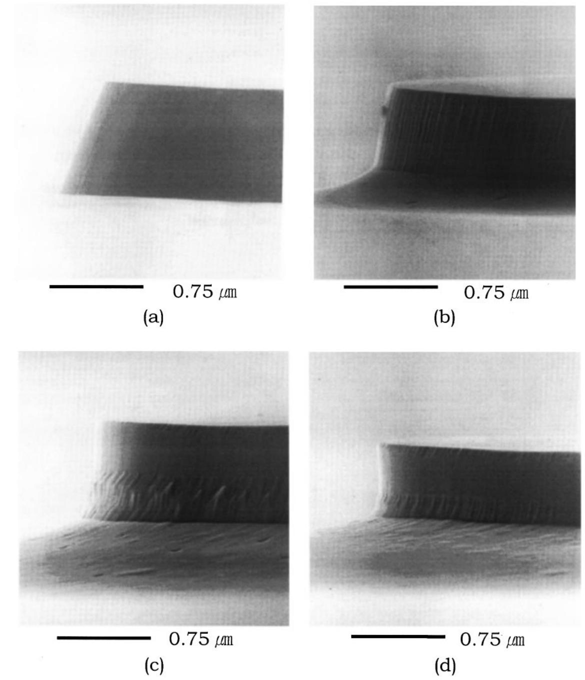

FIG. 2. GaN laser diode etch profile as a function of the tilt angle for 500 V/300 mA ion beam voltage/current, 6 sccm Cl_2 flow rate, and −20 °C substrate temperature. (a) 0°, (b) 30°, (c) 50°, and (d) 60°.

were distributed around the substrate through a nozzle. The reactive gas used in this experiment was Cl_2. The substrate was kept between −20 °C and room temperature while rotating the samples. The substrate was tilted from 0° to 60 °C. The tilt angle was measured between the substrate normal and the axis of the ion beam. The etch characteristics such as etch rates, etch selectivities, and etch profiles were estimated using a profilometer and scanning electron microscopy (SEM). The variation of the surface composition of the etched GaN samples was investigated using x-ray photoelectron spectroscopy (XPS). To evaluate the electrical properties of the etched GaN such as the ohmic contact resistivity, the transmission line method (TLM) was used. The ohmic contacts for the TLM were fabricated on the etched GaN by electron-beam evaporation of Ti–Al using a lift-off technique, followed by photoresist stripping and rapid thermal annealing.

III. RESULTS AND DISCUSSION

Figure 1 shows the effect of tilt angle on the GaN etch rates for 500 V/300 mA of ion beam voltage/current, 6 sccm of Cl_2 flow, and 20 °C substrate temperature. As shown in Fig. 1, the GaN etch rate increased with an increase of tilt angle to 30° and a further increase of the tilt angle decreased the GaN etch rate. A GaN etch rate of 1800 Å/min could be obtained at a 30° tilt angle. The etch selectivity over the conventional photoresist also increased with the tilt angle and showed 2.5 at a 20° tilt angle as a maximum. In general, the selectivity was higher than 1.5 for the tilt angle investigated in this study. The variation of the GaN etch rate with the increase of tilt angle appears to be related to the variation in sputter yield with the increase of tilt angle for the sputter etching. The tilt angle showing the maximum etch rate was different from that by pure physical sputter etching, possibly due to a chemical reaction such as the formation of volatile $GaCl_x$ involved in the CAIBE. The GaN etch rate shown in Fig. 1 is for *n*-GaN, and GaN etch rates for *p*-GaN, AlGaN, and InGaN were also investigated for 30° and 50° tilt angles for comparison. The GaN etch rates of *p*-GaN, AlGaN, and InGaN were similar to that of *n*-GaN for the experimental conditions used in this study.

Therefore, we investigated the etch profiles of a real GaN laser diode device that had a *p*-GaN/AlGaN/InGaN/AlGaN/*n*-GaN structure masked by a conventional photoresist as a function of tilt angle, and the result is shown in Fig. 2. The same etch conditions as those in Fig. 1 were used except for the substrate temperature. The substrate temperature used was −20 °C. The etch rate and the etch selectivity of GaN etched at −20 °C were similar to those etched at 20 °C. When the incident ion beam was perpendicular to the substrate, sidewall trenching due to ion scattering at the sidewall was observed, as reported by other researchers, and also a positively sloped GaN, etch profile possibly due to erosion of the photoresist mask was observed as shown in Fig. 2(a). An increase of tilt angle decreased the trenching up to a 20° tilt angle (not shown). A further increase of tilt angle, however, increased the possibility of etch tailing as shown at the bottom edge of the structures of Figs. 2(b)–2(d). This etch tailing appears to be from the shadowing effect of the ion beam due to the mask layer. As can be seen, the anisotropy of the GaN etch profile increased as the tilt angle was increased to 50°, where a vertical GaN etch profile was obtained. A further increase of the tilt angle to 60° showed a negatively sloped etch profile as shown in Fig. 2(d). The

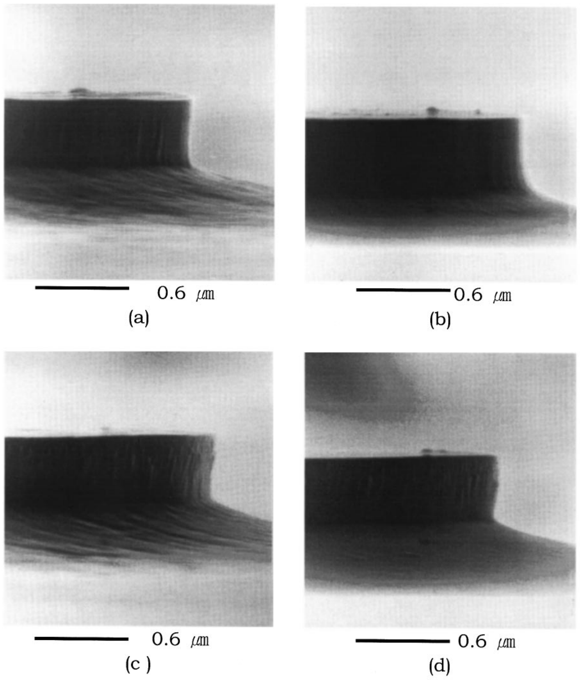

FIG. 3. Etch profiles of different materials used in the GaN laser diode. The materials were etched at 400 V/300 mA ion beam voltage/current, 8 sccm Cl_2, 50° tilt angle, and −20 °C substrate temperature. (a) *p*-GaN, (b) AlGaN, (c) InGaN, and (d) *n*-GaN.

change of etch slope with tilt angle appears to be related to the relative etch rate of the sidewall etching of the sloped photoresist and the sidewall etching of the GaN.

Some degree of sidewall roughness with Cl_2 CAIBE was observed at a tilt angle of more than 30° as shown in Figs. 2(c) and 2(d). To study the origin of the sidewall roughness, each of the different materials stacked in the real GaN laser diode was etched to examine the difference of the materials in sidewall roughness, and the result is shown in Fig. 3 for 400 V/300 mA ion beam voltage/current, 8 sccm Cl_2, 50° tilt angle, and −20 °C substrate temperature. The worst sidewall roughness was obtained with InGaN compared with *p*-GaN, *n*-GaN, and AlGaN. However, for the real device shown in Fig. 2, the thickness of InGaN was only a few hundred angstroms and the location of the rough sidewall did not exactly coincide with the location of the InGaN layer in the device; therefore, it may not be the source of the sidewall roughness shown above. Therefore, the real device structure was etched by varying the Cl_2 gas flow rate from 4 to 10 sccm at 500 V/300 mA of ion beam voltage/current, 50° tilt angle, and −20 °C substrate temperature. The degree of sidewall roughness was also examined using SEM and some of the results are shown in Fig. 4. The increase in Cl_2 gas flow increased the GaN etch rate when the Cl gas flow rate increased from 4 to 6 sccm, however, a further increase in the Cl_2 gas flow rate to 10 sccm saturated the GaN etch rate. Therefore, similar GaN etch rates were observed when the Cl_2 flow rate was varied from 6 to 10 sccm (not shown). As shown in Figs. 2(c), 4(a), and 4(b), an increase in the Cl_2 gas flow rate decreased the sidewall roughness without changing

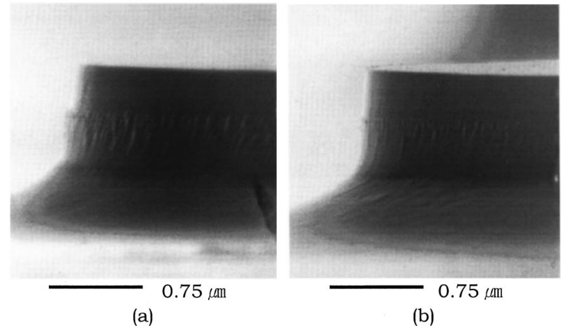

FIG. 4. GaN etch profile etched with 500 V/300 mA Ar ion beam voltage/current, 50° tilt angle, −20 °C substrate temperature, and (a) 8 and (b) 10 sccm Cl_2 flow rates.

the anisotropy of the etch profile. Also, a decrease of ion beam voltage appears to reduce the sidewall roughness even though the decrease of ion beam voltage decreased the GaN etch rate (not shown). Currently the exact reason for the source of the sidewall roughness shown in our experiment is not clear and it needs more investigation. However, it appears to be related to the increased sputter redeposition of etch products on the sidewall from the GaN wafer surface due to the high tilt angle rather than the difference in the materials in the device structure. Therefore, the increased chemical reaction at the higher Cl_2 flow rate and the lesser redeposition at the lower ion beam voltage appear to increase the sidewall smoothness of the real device.

A vertical etch profile with a very smooth sidewall could be obtained by optimization of the ion beam voltage/current and Cl_2 flow rate and the result is shown in Fig. 5. The GaN etch rate at the condition shown in Fig. 5 was 1000 Å/min.

During the etching of the real device structure, *n*-GaN is exposed to the ion beam. On the ion beam exposed *n*-GaN surface, an ohmic contact is fabricated by the deposition of metals. The change in the stoichiometry of the ion beam exposed *n*-GaN surface could cause changes in the ohmic contact resistance. Therefore, the effect of Cl_2 CAIBE on the composition of the etched *n*-GaN surface was investigated using XPS and the result is shown in Fig. 6 for the *n*-GaN etched at 500 V/300 mA ion beam voltage/current, 50° tilt angle, 6 sccm Cl_2, and −20 °C substrate temperature. The

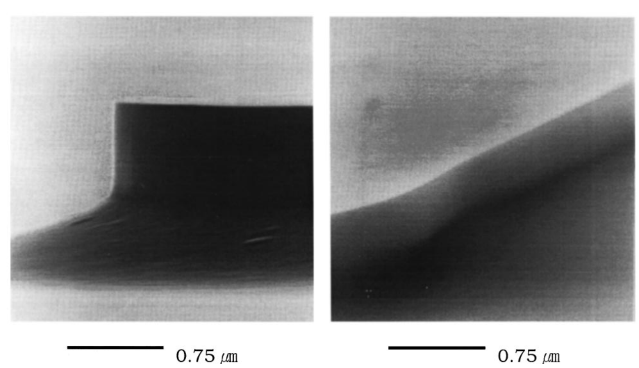

FIG. 5. GaN etch profile etched under the optimized conditions of Ar ion beam voltage/current and Cl_2 flow rate.

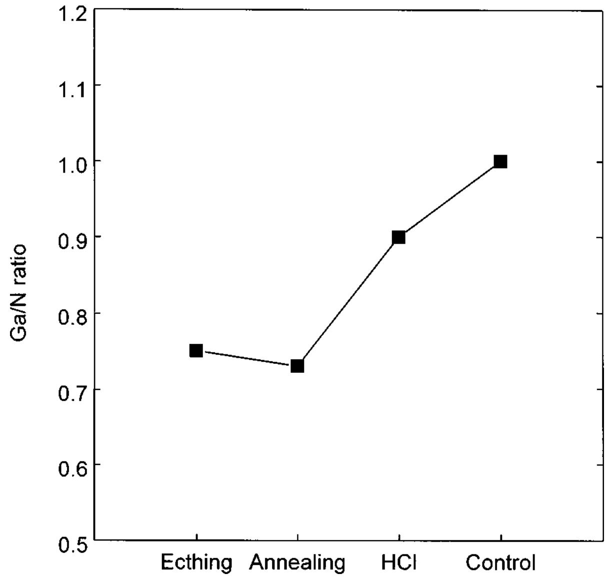

FIG. 6. Ga/N ratio of the etched GaN surface measured by XPS. Etch conditions: Ar ion beam condition/current 500 V/300 mA, tilt angle 50°, substrate temperature $-20\,°C$, and Cl_2 6 sccm flow rate.

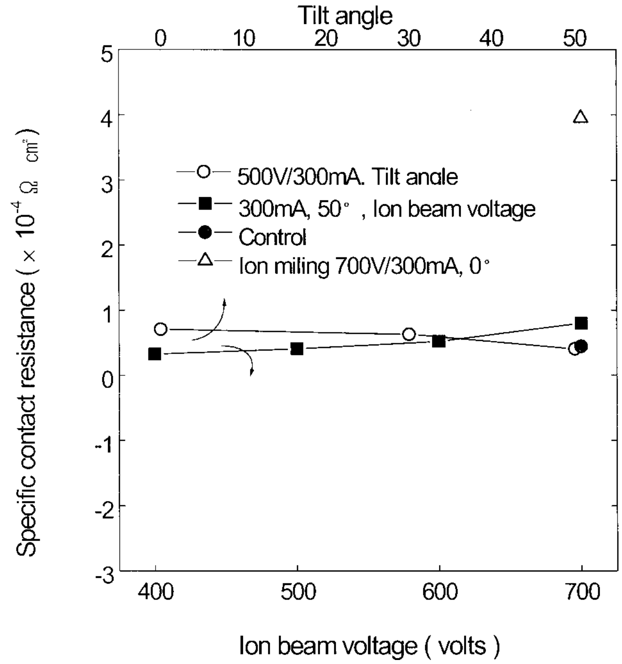

FIG. 7. Effects of ion beam voltage and tilt angle on the ohmic contact resistance of n-GaN etched at 300 mA ion beam current and $-20\,°C$ substrate temperature.

surface compositions of an unetched GaN and the etched GaN after an annealing and a HCl cleaning were included in Fig. 6. As is shown, the etched n-GaN showed a Ga-deficient surface. The variation in surface composition as a function of tilt angle and ion beam voltage was also investigated, however, in the case of Cl_2 CAIBE, the surface composition was still Ga deficient and did not change greatly with variation of the ion beam voltage and tilt angle (not shown). As shown in Fig. 6, the degree of Ga deficiency decreased after annealing and HCl cleaning was used as the postetch treatment before the deposition of Ti–Al metal layers.

After postetch treatments of variously etched n-GaN, ohmic contacts were formed by the deposition of Ti–Al metals followed by a rapid thermal annealing. A TLM pattern was used to characterize the ohmic contact resistance. Figure 7 shows the effects of ion beam voltage and tilt angle on the ohmic contact resistance of n-GaN etched at 300 mA of ion beam current and $-20\,°C$ substrate temperature. The ohmic contact resistance formed on unetched n-GaN and that formed on the GaN etched using Ar ion milling at 700 V/300 mA ion beam voltage/current and 0° tilt angle were included as references. As shown in Fig. 7, the ohmic contact resistance $(3-5\times10^{-4}\,\Omega\,cm^2)$ formed on the n-GaN etched by Ar ion milling was higher than that $(4-5\times10^{-5}\,\Omega\,cm^2)$ formed on the unetched GaN, possibly due to damage on the etched n-GaN. However, the contact resistance formed on the n-GaN etched at various ion beam voltages and tilt angles showed resistance $(4-6\times10^{-5}\,\Omega\,cm^2)$ similar to that formed on the unetched GaN regardless of the ion beam voltage and tilt angle used to etch the n-GaN. No significant effect of ion beam voltage and tilt angle on the ohmic contact resistance can be related to the Ga-deficient surface layer remaining on the etched n-GaN because it is reported that Ga-deficient n-GaN tends to form a low-resistance ohmic contact.[13]

IV. CONCLUSIONS

In this study, a GaN laser diode structure having a conventional photoresist as the etch mask was etched using Cl_2 CAIBE, and the etch properties were investigated as a function of tilt angle.

The n-GaN etch rate increased with the tilt angle and showed a maximum at a 30° of tilt angle, similar to the effect of physical sputter yield of sputter etching on tilt angle. Other materials such as p-GaN, AlGaN, and InGaN used for the GaN laser diode also showed similar etch rates as the n-GaN. The etch profile of the etched GaN laser diode structure changed from a positively sloped profile to a negative profile, and a vertical etch profile was obtained at a 50° tilt angle. Also, sidewall trenching was observed when the tilt angle was less than 20° due to ion scattering at the sidewall, and etch tailing was observed when the tilt angle was more than 30° due to shadowing by the etch mask and the etched structure. Sidewall roughness was observed when the tilt angle was more than 30°. Different sidewall roughness was observed when different materials used for the GaN laser diode were etched separately. An increase in the Cl_2 flow rate decreased the sidewall roughness of the GaN laser diode. A vertical GaN laser diode with a smooth sidewall was able to be fabricated by optimization of the ion beam voltage/current and Cl_2 flow rate.

Ohmic contacts fabricated on the n-GaN etched at various tilt angles and ion beam voltages showed similar resistance as those fabricated on the unetched n-GaN, therefore, no significant increase in the ohmic contact resistance was observed by the etching of GaN using Cl_2 CAIBE.

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