Fabrication of two dimensional GaN nanophotonic crystals (31)

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The authors have investigated chlorine based inductively coupled plasma etching of GaN by using different gas mixtures of Ar, Cl_2, and N_2. The etch mechanism and N_2 role have been studied. We found that both ion energy and ion current density are important. The N_2 plays a multiple role in etching GaN, chemical reaction, and ion bombardment. A reliable process to fabricate GaN nanophotonic crystals has been developed. Plasma conditions have been optimized toward a balance of ion current density, ion energy, and chemical species density. As a result, flat bottom, anisotropic photonic crystal with $a=215$ nm $d=129$ nm has been fabricated at an etch rate of 320 nm/min and an etch depth of 650 nm. For comparison, an etch rate of 530 nm/min has been obtained in etching trench lines down to 1.61 μm deep with a width of 500 nm. The developed process has been used to fabricate GaN photonic crystal (PC) waveguides for 1.55 μm wavelength. Transmission measurements reveal the $\mathbf{\Gamma M}$ stop band in hole type PC and illustrate the feasibility of the fabrication process. © *2007 American Vacuum Society.* [DOI: 10.1116/1.2794066]

INTRODUCTION

Photonic crystals (PCs) are increasingly drawing attention since the pioneering work of Yablonovitch.[1] GaN photonic crystals are especially interesting because of prospective improvement of the internal quantum efficiency, light extraction efficiency, and the directionality of GaN based light-emitting diodes[2] (LEDs) and novel PC lasers.[3] Shakya *et al.* suggested that further enhancement of light extraction efficiency can be achieved by improving the GaN hole anisotropy.[4] Wierer *et al.* reported that their photonic crystals to be tapered at an angle of 75° and suggested to etch deep holes to suppress unwanted off-axis scattering.[2] David *et al.* suggested azimuthally anisotropic photonic crystal for ultraefficient LEDs.[5] High aspect ratio etching of GaN nanostructures with a vertical profile, a smooth sidewall, and a flat bottom is essential for both LED and novel laser applications.

Several techniques have been used to study GaN dry etching by using reactive ion etching (RIE),[6] electron cyclotron resonance[7] plasma etching, inductively coupled plasma[8] (ICP) etching, and chemically assisted ion beam etching.[9] Different gas mixtures have been explored. Among them Cl_2 based ICP has been highly recommended for its high ion density[10] and has been extensively studied.[11] Etch rates of 833 nm/min in $N_2:Cl_2$ plasma and 820 nm/min in $Ar:Cl_2$ plasma in etching open area have been obtained.[8] Sheu *et al.*[8] concluded that appropriate ion bombardment is crucial for a workable etch rate and a vertical profile. Frick *et al.*[7] reported that optimization of the dry etch process can simply be done by using a low pressure Cl based RIE plasma with a relatively low N_2 content in the total gas flow.

However, all above mentioned studies dealt with large structures with small aspect ratios. Dry etching of high aspect ratio nanostructure, such as nanophotonic crystals, is totally different. Effects such as shadowing, chemical species transport, mask erosion, and electrostatic deflection of incoming ions in the holes make plasma etching of nanophotonic crystal structure very critical. Many efforts to solve the similar problems can be seen from numerous publications regarding InP nanostructure holes/pillar fabrication.[12] However, so far very little work in photonic crystals involving III-nitride materials has been reported partly due to the difficulty in fabrication[13] associated with the required nanometer scale periodicity.[10]

In this article, we study the etch mechanism for GaN nanostructures in $Ar:Cl_2$, $Ar:N_2:Cl_2$, and $N_2:Cl_2$ ICP plasmas in etching GaN nanostructures, with special attention for the beneficial role of nitrogen. Successful fabrication of azimuthally anisotropic GaN hole type photonic crystal struc-

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ture with a diameter of 129 nm, a lattice constant of 215 nm, and a depth of 650 nm is demonstrated. Preliminary optical measurement is presented and discussed.

EXPERIMENTS

The thickness range of GaN materials used in this study is from 650 nm to a few microns. A layer of 550 nm low stress SiN_x has been deposited by plasma-enhanced chemical vapor deposition on GaN samples. This SiN_x layer serves as a mask layer for GaN pattern transfer. Positive resist ZEP with a thickness of 500 nm baked at 175 °C for 30 min is used for the e-beam pattern definition with a EBPG5000$^+$ from Leica. The pattern transfer into the SiN_x mask layer has been carried out using a CHF_3/Ar RIE plasma. The details about how to obtain a clean and vertical profiled SiN_x mask have been published elsewhere.[13] The final pattern transfer into GaN has been carried out in an ICP system from Surface Technology System (STS). All ICP etching of GaN is performed at 40 °C, unless mentioned otherwise. Cl_2 is used as the main etching gas; Ar and/or N_2 are used as additive gases, while keeping the total gas flow rate at 40 SCCM (SCCM denotes cubic centimeter per minute at STP). Etch rates were determined from the depth of the etched features measured in a scanning electron microscope (SEM). The depth measurements are made on trench lines with a width of 500 nm.

For the optical experiments, 650 nm±200 nm GaN epilayer on sapphire with AlN buffer layer in between has been employed to confine the light into a single mode in vertical direction. The light has been polarized before coupled into the sample. The wavelength range of the light source is from 1470 to 1570 nm. Lithographic tuning[14,15] is employed to cover the photonic band gap given the limited tuning range of the laser. This means that transmission spectra of a series of PC structures with different lattice constants (a) are measured. For normalization and alignment purposes, ridge waveguides have been included in between the PC waveguides.

RESULTS AND DISCUSSION

Figure 1 shows etch rate and Vp.p. (peak to peak voltage) versus platen power in $30Ar:10Cl_2$ plasma. We vary platen power from 50 to 100 W. The other parameters are kept constant, i.e., Ar flow 30 SCCM, Cl_2 flow 10 SCCM, ICP source power 800 W, gas pressure 0.3 Pa, and etching time 5 min. The etch rate plotted is a time-averaged value over the interval because of apparent aspect ratio dependent etching. Vp.p. increases linearly with the platen power. Figure 1 shows that the etch rate is independent of the platen power. As ion yield does not increase with ion energy in the given ion energy range, the chemical component in the etch process seems to be the limiting factor. This could be either related to the supply of chemical reactant to the surface or due to a rate limiting step in the product formation itself. As GaN etching is strongly ion induced, the ion energy is suggested to be crucial for GaN bonding breaking as a most important step. Sheu *et al.* reported an abrupt etch rate enhancement around

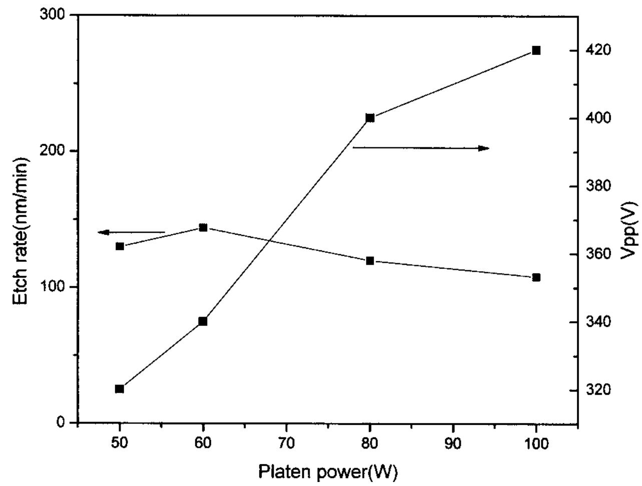


FIG. 1. Etch rate and Vp.p. (peak to peak voltage) vs platen power in $30Ar:10Cl_2$ plasma. For plasma experiment settings, see text.

190 eV in Cl_2/Ar ICP etching.[8] Rong *et al.*[13] observed a real ion energy threshold for Ar ions at 150 eV and about 100 eV for SF_6/N_2 plasma.

Next we consider ICP etch behavior in different gas mixtures. Results on trench etching are summarized in Figs. 2(a)–2(d); corresponding photonic crystal hole data are displayed in Figs. 3(a)–3(d). Etch data are collected in Table I.

Figure 2(a) shows the SEM image of trench lines etched by $30Ar:10Cl_2$ plasma with etch conditions of ICP source power 600 W, platen power 200 W, gas pressure 0.3 Pa, and etching time of 3 min. Three obvious phenomena are sloped sidewalls, trenching at bottom of sidewall, and no RIE lag. The sloped sidewall points to a sputter-dominated regime with limited volatility of etch products. In an ion-dominated process, lag is not expected, in agreement with the observation. The trenching is the result from angular distributed ions, collected at the bottom edges upon colliding with a sidewall. Also, when sidewall is tapered ions will increasingly collide at a glancing angle before they arrive at the surface. This gives a local increase in the etch rate called trenching.[16] Overall $30Ar:10Cl_2$ plasma is in the ion-limited regime. Figure 3(a) shows the corresponding hole type photonic crystal etched in GaN by the same $30Ar:10Cl_2$ plasma. The nanoholes are even more strongly tapered. It points to excessive difficulty to remove the etch products and this makes Cl_2/Ar process inappropriate for GaN nanophotonic crystal fabrication.

Figure 2(b) shows the SEM image of the same pattern etched by $25Ar:5N_2:10Cl_2$ ICP plasma with the same etching condition, as mentioned for Fig. 2(a). Noticeable differences with $30Ar:10Cl_2$ process performance are (1) no obvious trenching at the bottom of sidewall, (2) better verticality of profile, and (3) observable RIE lag. Taking the ratio of depths of 900 and 100 nm trenches as the RIE lag factor, its value is 1.8. Furthermore, the etch rate (260 nm/min) is substantially higher compared to that of $30Ar:10Cl_2$ plasma (180 nm/min), as shown in Table I. All observations (etch rate, etch profile, and RIE lag) point to a

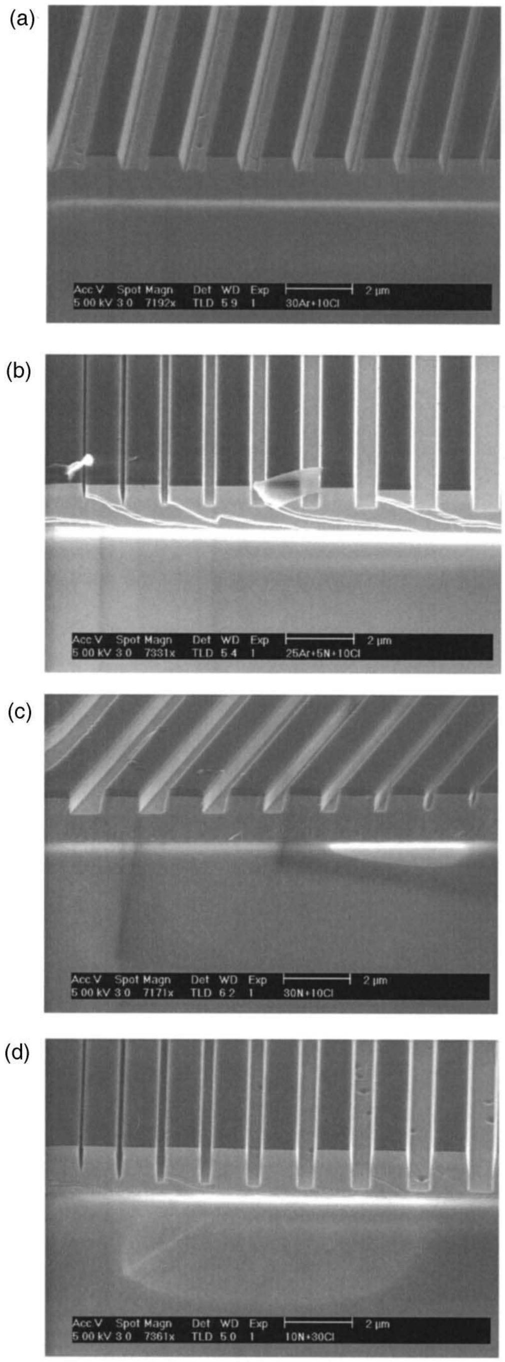


FIG. 2. SEM images of trench lines etched in (a) $30Ar:10Cl_2$, (b) $25Ar:5N_2:10Cl_2$, (c) $30N_2:10Cl_2$, and (d) $10N_2:30Cl_2$. For plasma experiment settings, see text. The samples are 60° tilted for imaging.

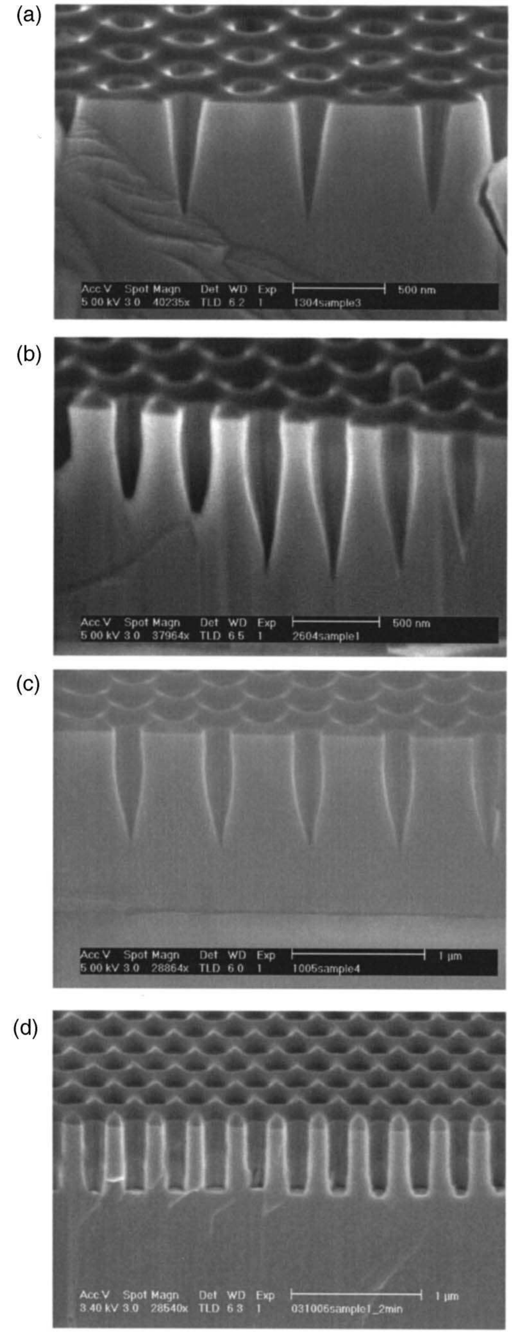


FIG. 3. SEM images of hole type photonic crystal etched in (a) $30Ar:10Cl_2$, (b) $25Ar:5N_2:10Cl_2$, (c) $30N_2:10Cl_2$, and (d) $10N_2:30Cl_2$. For plasma experiment settings, see text. The samples are 60° tilted for imaging.

largely improved balance of the ion flux (energy, current density) and the chemical particle flux in the plasma. With practically the same ion flux compared to the $30Ar:10Cl_2$ process (820 V vs 850 V, same platen power), it points to chemical involvement of the small N_2 component in the etch mechanism. The results are consistent with the etch rate enhancement observed for GaN in $SF_6:N_2$ ICP plasma[13] and etch acceleration of Si_3N_4 in $CHF_3:N_2$.[17] It is suggested that N radicals from the plasma attack the nitride surface under formation of molecular N_2. In this way, a reaction path with lower energy barrier is opened. As the etch profile does not show any indication of underetch, the overall mechanism is still ion induced. Altogether the N_2 addition yields a smooth ion-induced etch process with a more anisotropic profile. However, the lag observed for higher aspect ratio points to depletion of the small nitrogen gas component in small structures and so less etch rate enhancement.

Figure 2(c) shows the SEM image of structures etched by $30N_2:10Cl$ plasma at the same etch condition, as mentioned

TABLE I. Etch characteristics of GaN in different Cl based plasmas. The etch rates are resulted from 500 nm trench line.

Gas Mixture	*V*p.p. (V)	Etch rate (nm/min)	RIE lag factor[a]	Profile of PC hole	Trenching at bottom
$30Ar:10Cl_2$	820	180	1	Tapered	Yes
$25Ar:5N_2:10Cl_2$	850	260	1.8	Less tapered	No
$30N_2:10Cl_2$	1160	250	1.2	Anisotropic	No
$10N_2:30Cl_2$	950	530	2	Azimuthally anisotropic	No

[a]Ratio of the depth of 100 nm line to the depth of 900 nm.

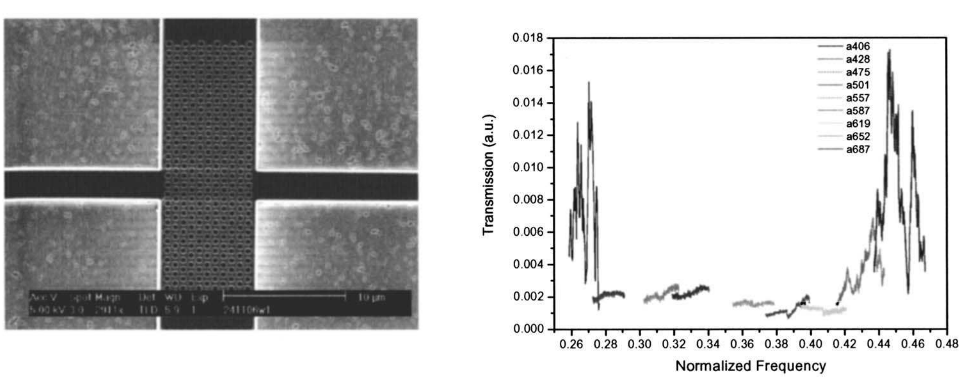
for Fig. 2(b). The noticeable difference is the slightly decreased etch rate, 250 nm/min (Table I) and smaller lag (RIE lag factor=1.2). Figure 3(c) shows the corresponding nanohole profile. It turns out that the anisotropy slightly improved compared to the hole profile shown in Fig. 3(b). It is conjectured that angular distribution of the ions is somewhat less due to a higher ion energy (Vp.p. of 1160 V vs 850 V). Because of the larger supply of N_2, the depletion at the bottom of high aspect ratio structures decreases and so the lag. The slightly lower etch rate (250 nm/min compared to 260 nm/min) is the result of several factors. On the one hand, the higher ion energy in parallel to a larger N_2 component for the chemical enhancement will favor the etch rate. On the other hand, the much higher ion energy (Vp.p. of 1160 V vs 850 V) at the same platen power points to a lower ion current density and so a lower etch rate. Apparently the etch regime in the $30N_2:10Cl_2$ process is ion limited.

Figure 2(d) is a SEM image of structures etched in a $10N_2:30Cl_2$ plasma at the same etching conditions, as mentioned for Fig. 2(c). Anisotropic features and RIE lag (RIE lag factor=2) are the most obvious phenomena. The etch rate comes to a maximum (530 nm/min) among all the experiments. The high etch rate results from the improved balance of the ion flux (energy and density) and the largely increased reactive Cl flow. The severe RIE lag in the $10N_2:30Cl_2$ process suggests feature size dependent transport of chemical species to be the rate limiting factor. Further optimization of the balance might be obtained by tuning the Cl_2/N_2 ratio. A flat bottom photonic crystal with $a=215$ nm and $d=139$ nm, so called azimuthally anisotropic photonic crystal has been fabricated. An etch rate of 350 nm/min for a nanohole depth of 650 nm has been achieved, as shown in Fig. 3(d). Here, the plasma condition has been optimized into a regime of balanced ion current density, ion energy, and chemical species for this dimension of structures. For larger features the balance will be different and bowing phenomena may occur with this etch condition. An appropriate adjustment will be required for the structures with different dimensions. It could be problematic to combine micron size waveguides and nanophotonic crystal building blocks in a single pattern.

To demonstrate the feasibility of the etch technology for GaN PC structures, we have fabricated and characterized the GaN PC waveguides by optical transmission measurement. Figure 4(a) shows the top view of a PC waveguide device. Figure 4(b) shows transmission spectra of GaN PC waveguide in hole type photonic crystal. Every color in the spectrum represents a measurement trace of one lattice constant. Two PC waveguide structures turned out to be damaged and thus two empty spaces are in the spectrum. The $\Gamma\mathbf{M}$ stop band with the designed r/a ratio of 0.3 has been obtained.[18] The observation of the band gap behavior highlights the good quality of the fabrication achieved and launches the field of photonic band gap engineering in gallium nitride and its related semiconductors.

CONCLUSIONS

We have studied etching of GaN in Cl_2 based ICP plasmas. The etching mechanism is discussed and unraveled. Appropriate balance of physical and chemical fluxes is essential



(a) (b)

FIG. 4. Top view of GaN photonic crystal waveguide (a) and corresponding photonic crystal band gap with distinct dielectric and air band.

for workable etch rates and anisotropic profiles. This delicate balance is even more stringent when high aspect ratio nanostructures are to be realized. Throughout a relatively high ion energy is needed to initiate the Ga–N bond breaking as a first step. N_2 addition to the gas mixture apparently facilitates this step. The ICP plasma with $10N_2:30Cl_2$ has been optimized into a regime of balanced ion energy, ion density, and chemical species density to achieve azimuthally anisotropy photonic crystal hole with $a=215$ nm and $d=139$ nm with ICP source of 600 W, platen power of 200 W, and working pressure of 0.3 Pa. The etch rate of 350 nm/min and depth of 650 nm for such a nanostructure has been demonstrated. The etch rate of 530 nm/min has been obtained in etching trench line down to 1.61 μm deep with a width of 500 nm. The developed process has been applied to fabricate the photonic crystal waveguides; $\mathbf{\Gamma M}$ stop band has been obtained. This further confirms high quality of the photonic crystals and the technology developed.

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