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Selective dry etching of III-nitrides in inductively coupled plasmas

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Abstract A parametric comparison of etch rate and etch selectivity has been performed for GaN, InN and AlN etched in chlorine- and boron halides-based Inductively Coupled Plasma (ICP) discharges. Chlorine-based chemistries produced controllable etch rates (50~150 nm/min) and maximum etch selectivities ~6 for InN over GaN and ~10 for InN over AlN. Maximum etch selectivities of ~100 for InN over GaN and InN over AlN were obtained in boron halides-based discharges and smooth etched surface morphologies were also achieved.

1. Introduction

Due to the chemical inertness and high bond strength of the III-nitride materials, high density plasma etch techniques have played a critical role in fabricating photonic devices such as light-emitting diodes (LEDs) or laser diodes [1, 2]. Attention is now turning to the development of GaN-based high power/high temperature electronics for power switching and transmission applications [3-7]. The etching requirements are quite different for these devices, with the etch depths being much shallower. In III-nitride-based electronic device technologies such as heterostructure field effect transistors, heterostructure bipolar transistors, and various thyristor structure, highly selective removal of one nitride layer from other nitride layers is required since InN-based layers are expected to be used as contact layers with low contact resistance, in analogy to InGaAs on GaAs [8-10].

In this paper we report a comparison study on ICP etching of GaN, AlN and InN with chlorine- and boron halides-based plasma chemistries. Boron halides (BI_3 and BBr_3) mixtures were found to be very promising chemistries that allow the full range of desired etching properties, i.e. non-selective, selective for InN over GaN and AlN, while chlorine-based chemistries produced controllable etch rates (50~150 nm/min) and reasonable selectivities (~6 for InN over GaN and ~10 for InN over AlN).

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2. Experimental

1-3 μm thick epitaxial layers of GaN, InN and AlN were grown on α-Al_2O_3 by either Metal Organic Chemical Vapor Deposition (MOCVD for GaN) at 1040°C or by Metal Organic Molecular Beam Epitaxy [11] (MOMBE for InN and AlN) at 600°C and 800°C, respectively. The layers were nominally undoped ($n \sim 6\times10^{16}$ cm^{-3} for GaN, $n \sim 10^{20}$ cm^{-3} for InN and resistive, $>10^{8}$ Ω·cm, for AlN). The samples were patterned with photoresist or SiN_x. Etching was performed in a Plasma Therm ICP 790 system utilizing a 3 turn coil ICP source operating at 2 MHz and powers up to 1500 W. The samples were thermally bonded to a Si carrier wafer that was mechanically clamped to a He backside cooled, rf powered (13.56 MHz, up to 450 W) chuck. The BI_3 and BBr_3 were contained in a vacuum vessel heated to ~45°C to increase their vapor pressure. Etch rates were obtained from stylus profilometry after removal of mask materials. The surface morphology and surface roughness of selected GaN samples were examined with Scanning Electron Microscopy (SEM) and Atomic Force Microscopy (AFM). Etch selectivity was calculated for InN over GaN and AlN.

3. Results and Discussion

Figure 1 shows the nitride etch rates (top) and selectivity for InN over GaN and AlN (bottom) as a function of ICP source power at fixed dc self-bias (-100 V) and plasma composition ($10Cl_2/5Ar$). The nitride etch rates increase as ICP source power increases

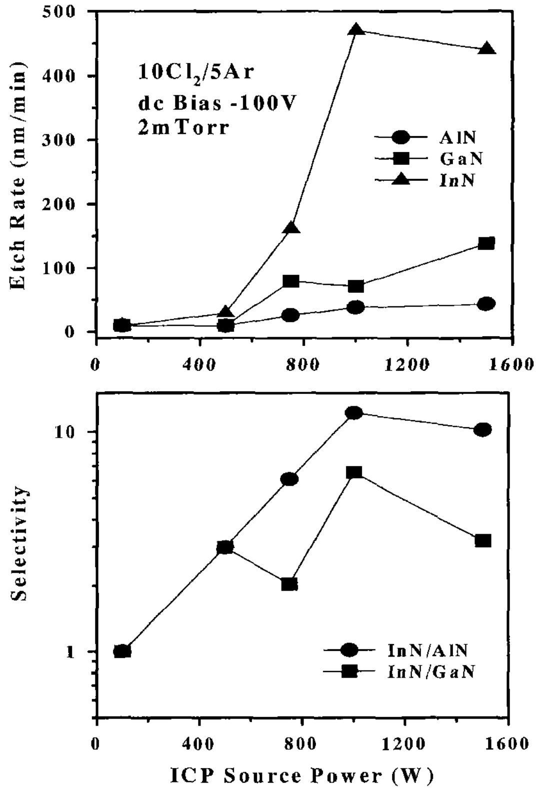

Fig. 1. Nitride etch rates (top) and selectivities for InN/AlN and InN/GaN (bottom) in $10Cl_2/Ar$ ICP discharges (-100 V dc self-bias, 2 mTorr) as a function of source power.

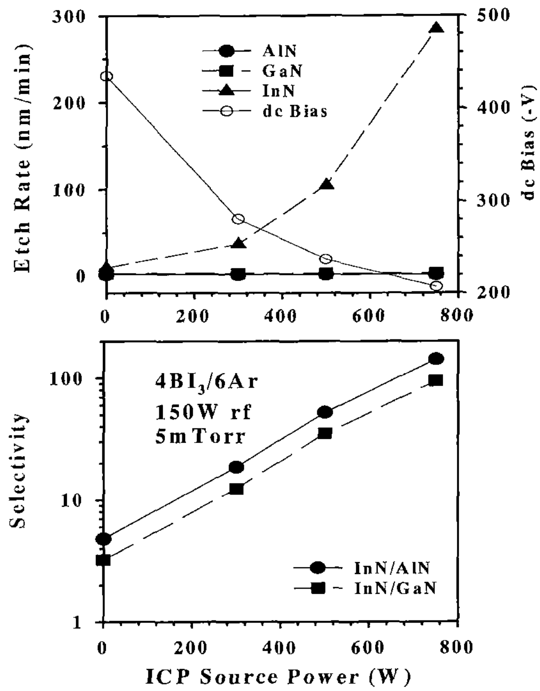

Fig. 2. Nitride etch rates (top) and selectivities for InN/AlN and InN/GaN (bottom) in $4BI_3/Ar$ ICP discharges (150 W rf chuck power, 5 mTorr) as a function of source power.

by increasing the ion flux and atomic chlorine density in the plasma [12]. The results for InN are similar to what we observe in high density plasma etching of InP [13]. There is a sharp rise in etch rate above a particular source power, which we ascribe to the prevention of formation of an $InCl_3$ selvedge layer which normally retards further etching [14, 15]. At source powers above 1000 W, further increases in ion flux do not increase the InN etch rate due to the ion-assisted removal of reactive chlorine neutrals before they can form the $InCl_x$ etch product on the surface. GaN and AlN show a general trend of increasing etch rate across the entire range of ICP source powers. It is clear that at source powers below 750 W, selectivities of only around 2 are obtained for InN over GaN, whereas etch selectivities for InN over GaN increase to about 6 for higher powers (1000 W), and maximum etch selectivities of ~10 are obtained for InN over AlN.

In high density plasma sources, ion density is basically controlled by the power applied to the source, while ion energy is mostly dependent on applied rf chuck power. Figure 2 shows the InN etch rate (top) is monotonically dependent on source power, indicating the presence of a strong chemical component to its etching while GaN and AlN show low etch rates due to their higher bond energies than that of InN (7.72 eV/atom compared to 8.92 eV/atom for GaN and 11.52 eV/atom for AlN). The resultant etch selectivities (bottom) for InN over AlN and InN over GaN increase with source power and reache ~100 at 750 W source power.

Similar data are shown in Fig. 3 as a function of ICP source power for $4BBr_3/6Ar$ discharges. Under these conditions the etch rate of InN continues to increase with source power, which controls ion flux. Note that the InN etch rates are approximately a factor of two lower in BBr_3/Ar compared to BI_3/Ar (Fig. 2, top) even for the lower rf chuck powers. This is expected from a consideration of the relative stabilities of the respective In etch products (InI_3 melting point 210°C; $InBr_3$ sublimes at <600°C). InN etch rates are lower than with BI_3/Ar, and therefore selectivities of ~30 for InN over AlN and ~40 for InN over GaN were obtained. There is a minimum in the InN over GaN data around 750 W source power, which may result from a competition

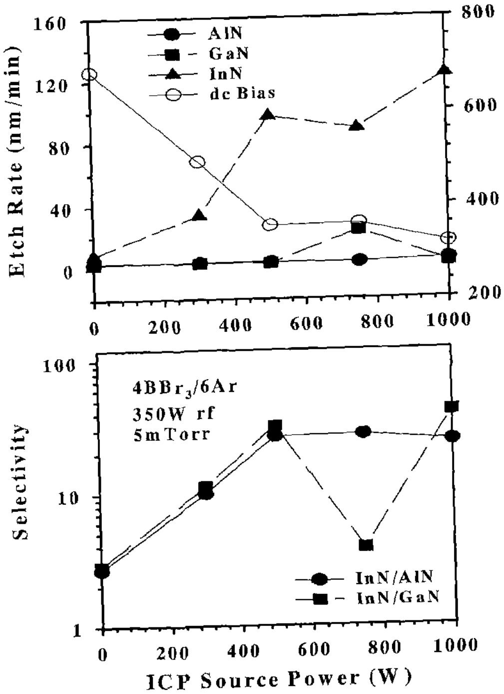

Fig. 3. Nitride etch rates (top) and selectivities for InN/AlN and InN/GaN (bottom) in $4BBr_3/Ar$ ICP discharges (350 W rf chuck power, 5 mTorr) as a function of source power.

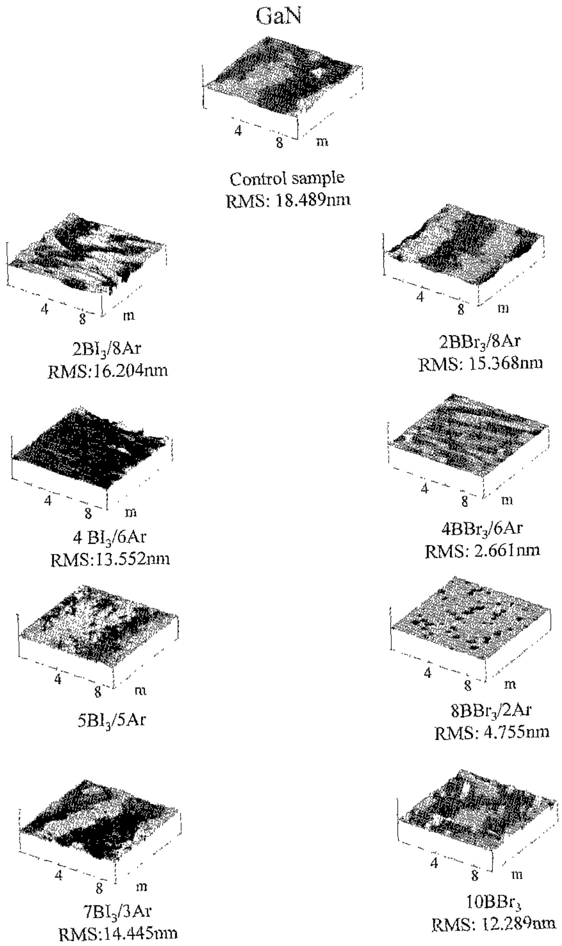

Fig. 4. AFM scans of GaN surfaces before and after etching in BI_3/Ar (750 W source power, 150 W rf chuck power, left) or BBr_3/Ar (750 W source power, 350 W rf chuck power, right) discharges as a function of plasma composition.

between increased etch rate of GaN due to higher flux, and desorption of the active bromine by ion-assistance at still higher fluxes.

One feature of the etching in boron halides-based discharges is smooth etched surface morphologies were obtained. Figure 4 shows examples of AFM scans ($10\times10\ \mu m^2$) of GaN before and after etching and GaN root-mean-square (RMS) roughness dependence on discharge composition for BI_3 and BBr_3 chemistries is shown in Fig. 5. The most important result is that all of the etched surfaces have lower RMS roughness values than the unetched control sample. This type of surface smoothing has been reported previously for GaN [16], and ascribed to the angular dependence of ion milling rates producing faster removal of sharp features.

4. Conclusions

Inductively Coupled Plasma etching with Cl_2/Ar discharges is able to produce practical etch rates for GaN, InN and AlN (i.e. 50~150 nm/min) at low dc self-biases (100 V) where conventional reactive ion etching is impractically slow. The etch rates are a strong function of high density source power and maximum etch selectivities ~6 for InN over GaN and ~10 for InN over AlN were obtained.

BI_3 and BBr_3 discharges also produced practical etch rates for GaN, InN and AlN, and under optimum conditions etch selectivities of ~100 for InN over AlN and GaN were achieved. These are the highest values reported for high density plasma conditions, and result from the good volatility of InI_x etch products. The etched GaN and InN samples showed good surface morphologies, having similar or even lower RMS roughness values than the unetched control sample. Both of these

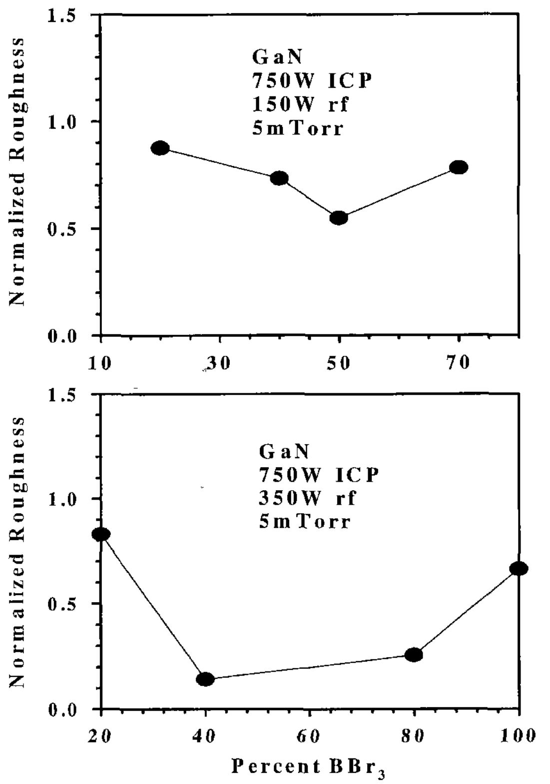

Fig. 5. Dependence of GaN normalized etched surface roughness on boron halide percentage in BI_3/Ar (top) or BBr_3/Ar (bottom) discharges.

plasma chemistries appear useful for selective etch processes in nitride electronic device fabrication.

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