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SAND098-0662C

Low Damage, Highly Anisotropic Dry Etching of SiC SAND-98-0662C

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REVIEWED

16 1998

CONF-980622-1
J. STI

ABSTRACT: A parametric study of the etching characteristics of 6H p⁺ and n⁺ SiC and thin film SiC_{0.5}N_{0.5} in Inductively Coupled Plasma NF₃/O₂ and NF₃/Ar discharges has been performed. The etch rates in both chemistries increase monotonically with NF₃ percentage and rf chuck power. The etch rates go through a maximum with increasing ICP source power, which is explained by a trade-off between the increasing ion flux and the decreasing ion energy. The anisotropy of the etched features is also a function of ion flux, ion energy and atomic fluorine neutral concentration. Indium-tin-oxide (ITO) masks display relatively good etch selectivity over SiC (maximum of ~70:1), while photoresist etches more rapidly than SiC. The surface roughness of SiC is essentially independent of plasma composition for NF₃/O₂ discharges, while extensive surface degradation occurs for SiCN under high NF₃/O₂ conditions.

INTRODUCTION: There has been a revival of interest in SiC-based high power, high temperature (>250°C) devices and circuits for applications ranging from advanced avionics, automobiles, and space exploration to bore-hole logging.⁽¹⁻⁴⁾ SiC is the most mature of the candidate semiconductors, which include diamond and GaN, and has the advantage of high thermal conductivity and availability in both bulk, single-crystal and thin-film form. The two most common polytypes are 6H and 4H, although cubic material (3C) is also available⁽³⁾. There are a wide variety of device structures that have been fabricated in 6H, including thyristors, static induction transistors, Schottky diodes, metal-semiconductor field effect transistors (MESFETS) and various vertical Metal-Oxide-Semiconductor (MOS) devices.⁽¹⁻⁴⁾

In all of these structures there is a need for pattern transfer capability. While some success has been obtained with photo-chemical etching in electrolytes that oxidize the SiC surface and subsequently dissolve this oxide,^(5,6) it is generally agreed that conventional wet chemical etching is not possible at practical temperatures. This places a strong emphasis on development of high quality dry etch processes. Most of the plasma etching to date has been performed with capacitively-coupled reactors, particularly reactive ion etching (RIE), with fluorine-based gas chemistries.⁽⁷⁻¹³⁾ One attribute of this technique is the high ion energy (typically ≥ 200 eV), which is useful in breaking the bonds in the SiC. However a downside to high ion energies is mask erosion and residual lattice damage in the semiconductor. The etch products with fluorinated plasma chemistries are SiF_x and CF_x species, and under high bias conditions (i.e. physically-dominated process) these probably do not need to be fully fluorinated (i.e. x=4) to be desorbed from the surface by ion assistance. Alternative plasma chemistries include Cl₂-, Br₂- or I₂-based gases, but these produce slower etch rates than the F₂-based mixtures. Rather than rely simply on high ion energy to stimulate etching of the SiC, another approach is to employ a high ion flux with lower ion energy.⁽¹⁴⁻²¹⁾ This is the basis of the newer high density plasma tools in vogue for pattern transfer in Si. Etching of SiC in Electron Cyclotron Resonance (ECR)^(14,20) and Inductively Coupled Plasma (ICP)⁽²¹⁾ reactors has been reported by several groups, with fairly good etch rates and good anisotropy. The operating pressure (1-2 mTorr) of these tools is much lower than in RIE systems (10-300 mTorr), with much higher ion fluxes ($\geq 10^{11}$ cm⁻³ compared to $\geq 10^9$ cm⁻³). A major

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advantage with the newer reactors is the ability to separately control ion flux and ion energy, leading to increased flexibility in designing etch products.

In this paper we report a parametric investigation of the etching characteristics of 6H-SiC bulk wafers and thin film SiCN in ICP NF₃-based plasma chemistries. The removal rate of both SiC and SiCN and etch anisotropy is found to be a function of atomic fluorine neutral density, ion flux and ion energy. The resulting surface roughness is almost independent of plasma composition for SiC, but for SiCN surface morphology degrades at high NF₃ percentages in the gas feedstock. The surfaces are chemically clean over a wide range of conditions, with only small concentrations of either N- or F-containing residues detected.

EXPERIMENTAL: The SiC samples were bulk substrates doped with either Al ($p = 6 \times 10^{18} \text{ cm}^{-3}$) or N ($n \sim 5 \times 10^{18} \text{ cm}^{-3}$), and both with (100) orientation. The SiC_{0.5}N_{0.5} layers were grown on Si substrates using chemical vapor deposition with a tris-dimethylamino silane precursor, and were $\sim 5,000 \text{ \AA}$ thick and nominally undoped. All of the experiments were performed in a Plasma Therm 790 system. The samples are located on a He backside cooled chuck biased with 13.56MHz of power. Etch rates were obtained from stylus profilometry measurements of the samples after mask removal. Scanning Electron Microscopy (SEM) was used to examine etch anisotropy and surface morphology, while Atomic Force Microscopy (AFM) was employed to quantify the surface roughness. Optical Emission Spectroscopy (OES) was used to monitor plasma species.

RESULTS AND DISCUSSION: Figure 1 shows SiC and SiCN removal rates as a function of NF₃ percentage in NF₃/O₂ and NF₃/Ar for fixed source power, pressure and rf chuck power. There are several interesting aspects of the data. First, the rates are slightly higher with NF₃/Ar, which suggests that ion bombardment plays a role in the etch mechanism. Since the etch products (SiF_x and CF_x, where $x \leq 4$) are quite volatile, it is likely that more efficient bond-breaking in the SiC rather than ion-enhanced desorption of these products, is the reason for this trend. Second, there is no measurable difference in etch rates between n⁺ and p⁺ SiC, indicating that Fermi level effects play no role in the etch mechanism. Third, the etch rates increase

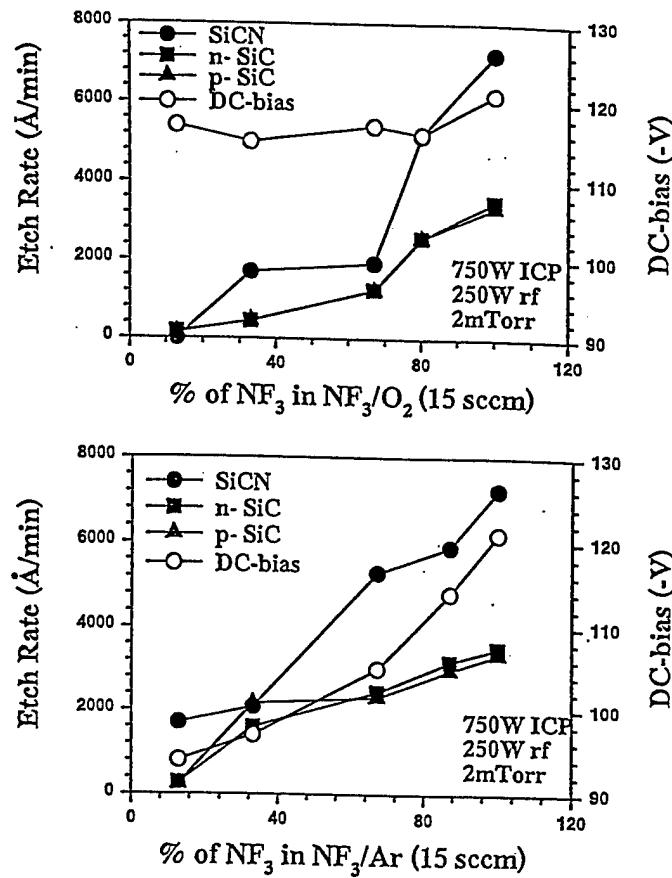


Figure 1. Etch rates of p⁺ SiC, n⁺ SiC and SiCN in 750W source power, 2mTorr, 250W rf chuck power discharges as a function of NF₃ percentage in either NF₃/O₂ (top) or NF₃/Ar (bottom).

monotonically with NF₃ percentage in both chemistries, which indicates that the limiting step is supply of atomic fluorine to the surface under these conditions. Fourth, the rates for SiCN are significantly higher than for SiC in both plasma chemistries, probably due to the high vapor pressure of the NF_x etch products and to the probable lower crystalline quality of the thin film SiCN relative to the bulk SiC, which is grown at much higher temperatures. Fifth, there is a finite etch rate for both materials in NF₃/Ar even at the lowest NF₃ percentage, whereas there is a threshold concentration for the commencement of etching in NF₃/O₂ discharges. Sixth, the behavior of dc self-bias with plasma composition is quite different in the two plasma chemistries. While it stays relatively constant in NF₃/O₂ suggesting that ion density also remains approximately constant, there is a monotonic increase with NF₃ percentage in NF₃/Ar. In the latter case this indicates that the conductivity of the plasma is decreasing as NF₃ increases, leading to a

higher self-bias. The associated higher ion energy is also a contributing factor to the higher etch rates with NF_3/Ar relative to NF_3/O_2 .

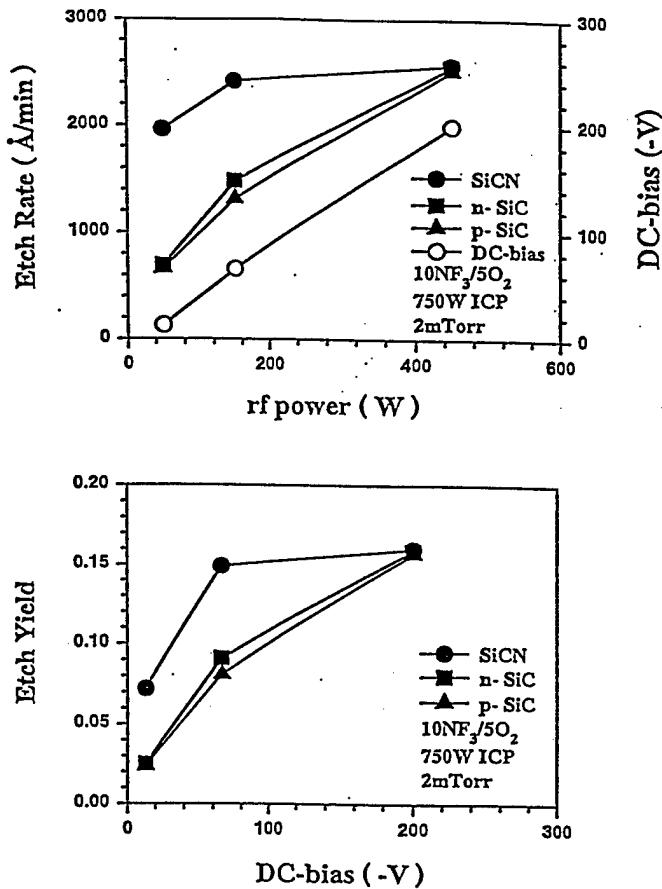


Figure 2. Etch rates of SiC and SiCN as a function of rf chuck power in $10\text{NF}_3/5\text{O}_2$, 2mTorr, 750W source power discharges (top) and etch yield of the same materials as a function of dc chuck self-bias (bottom).

Figure 2 shows etch rates as a function of rf chuck power (top) and etch yield as a function of dc self-bias (bottom). For SiC there is a monotonic increase in etch rate with bias, which again emphasizes the strong role of ion energy in the etch mechanism. The average ion energy is the sum of the dc self-bias voltage and plasma potential (roughly $\sim 20\text{V}$ in this tool). For SiCN the etch rate saturates as this bias is increased and this may be related to sputter-induced removal of the atomic fluorine before it can react with the surface. Note that the etch yields indicates are relatively low, but the resulting etch rate is high because of the high ion flux.

Figure 3 shows the dependence of etch rates on ICP source power (top) and the etch yield versus ion flux (bottom). As the source power is increased at constant rf chuck power, the dc self-bias is strongly suppressed

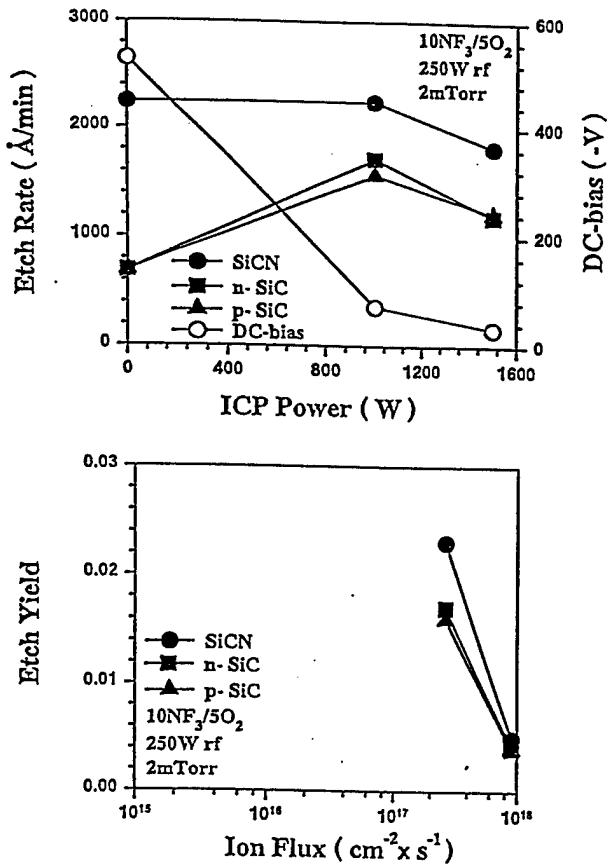


Figure 3. Etch rates of SiC and SiCN as a function of source power in $10\text{NF}_3/5\text{O}_2$, 2mTorr, 250W chuck power discharges (top) and etch yield of the same materials as a function of ion flux (bottom).

and the competing factors of increasing ion flux and decreasing ion energy produce the resulting maximum in etch rate at $\sim 1000\text{W}$ source power. Note that the etch rate for SiC can still be above $1,000\text{\AA}/\text{min}$ even at very low bias values provided the ion flux is high.

The surface roughness of both SiCN and SiC was examined after etching by AFM. The plasma composition dependence of root-mean-square (RMS) roughness is plotted in Figure 4 for SiCN, n^+ SiC and p^+ SiC. The values for SiCN go through a minimum at $\sim 33\%$ NF_3 by flow in NF_3/O_2 , and become very high as the NF_3 percentage is increased. We did not perform Auger Electron Spectroscopy (AES) in these samples, but we suspect that the surface becomes non-stoichiometric through preferential loss of one of the lattice constituents (probably N because NF_3 is the most volatile of the prospective etch products). The SiC samples showed stoichiometric surfaces over the whole range of plasma compositions, with very small

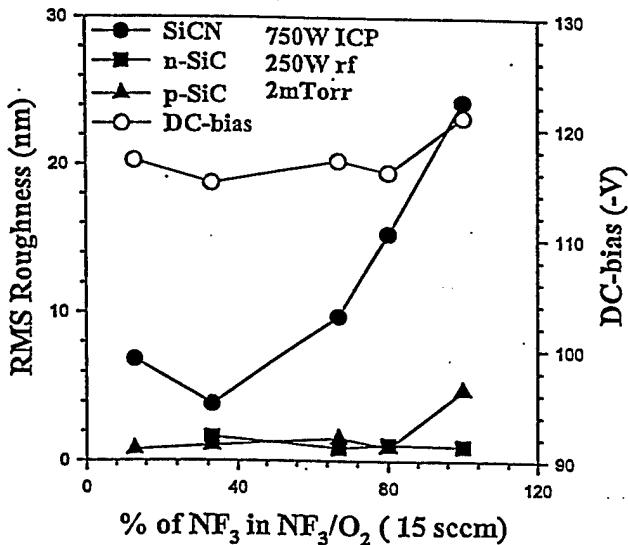


Figure 4. RMS roughness of SiC, n⁺ and p⁺ SiC measured by AFM after etching in NF₃/O₂ discharges (750W source power, 250W rf chuck power, 2mTorr) as a function of plasma composition.

quantities (≤ 0.2 at%) of N- or F- containing residues in some cases. This indicates that Si and C are being removed at equal rates under a wide range of conditions and that the etch products, once formed, are readily leaving the surface.

A final issue of practical interest in the etch selectivity of the SiC with respect to the two mask materials, photoresist and ITO. Figure 5 shows this

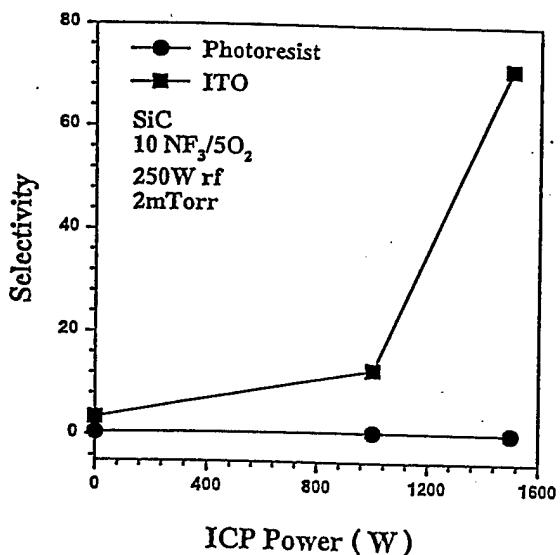


Figure 5. Etch selectivity for SiC relative to ITO and photoresist as a function of ICP source power in 10NF₃/5O₂, 250W chuck power, 2mTorr discharges.

data as a function of source power in 10NF₃/5O₂, 2mTorr, 250W rf chuck power discharges. As expected there is no selectivity with respect to photoresist, but the ITO has excellent etch resistance,⁽²⁰⁾ which increases as source power is increased due to the associated reduction in ion energy. A basic problem with dry etching of SiC is that the F-based chemistries which are most effective have poor selectivity for SiO₂, SiN_x and resist, requiring the use of non-standard mask materials.

SUMMARY AND CONCLUSIONS: ICP NF₃-based discharges produce smooth pattern transfer in SiC and SiCN at high rates (~3,500 Å/min in both n⁺ and p⁺ SiC, and ~7,500 Å/min in SiCN thin films.) The surface morphology of SiC was essentially independent of plasma composition in NF₃/O₂ discharges, but SiCN was much more sensitive to the atomic fluorine concentration. The etch rates of both SiC and SiCN were strong functions of ion flux, ion energy and fluorine concentration. This is consistent with the idea that the initial bond-breaking in the materials is an important step in the etch mechanism and this is enhanced at high ion fluxes and ion energies. Provided that there are sufficient weakened or broken bonds available for atomic fluorine to bond to, then the concentration of this reactant becomes the limiting step. The advantage of using NF₃ is that it is more readily dissociated than CF₄ or SF₆ and the combination with an ICP source means that ion energy, ion flux and atomic neutral density can be readily adjusted to produce high fidelity pattern transfer.

ACKNOWLEDGMENTS: The work of UF is partially supported by a DARPA grant (A.Husain) monitored by AFOSR (G.Witt) and by a DARPA/EPRI grant (E.R.Brown, J.Melcher). Sandia National Laboratories is a multiprogram laboratory operated by Sandia Corporation for Lockheed-Martin under DOE contract DE-AC04-94AL85000.

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M98004235



Report Number (14) SAAD--98-0662C
Conf- 980622 --

Publ. Date (11) 199803
Sponsor Code (18) DOE/DP ; DOE/CR, XF
UC Category (19) UC-705 ; UC-900, DOE/ER

DOE