Materials Science Forum Vols. 264-268 (1998) pp. 829-832
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Fast and Anisotropic Reactive Ion Etching of 4H and 6H SiC in NF_3

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Keywords: Reactive Ion Etching, NF_3, Etch Rate, Anisotropy, Roughness

Abstract. Reactive ion etching of the 4H- and 6H-SiC polytypes in an NF_3 plasma under conditions which produce both a high etch rate and highly anisotropic profiles is presented. The effects of flow rate, pressure and power on etch rate and self-induced DC bias are evaluated. Optimum RIE conditions of 80 sccm, 80 mTorr and 300 W (0.6W/cm^2) produce an etch rate of ~1200-1250 Å/min for both polytypes, while generating a DC bias of only ~100V. Under these conditions highly anisotropic profiles and residue-free etch fields are obtained. The roughness of the etched surface as measured by AFM was essentially similar to that of the as-received surface (~3Å).

1. Introduction

SiC device fabrication employs plasma-based etching techniques for structure patterning. Most such etching is performed in fluorinated plasmas usually under reactive ion etching (RIE) conditions, utilizing such gases as CF_4, SF_6, CHF_3, NF_3 or gas mixtures consisting of one or more fluorinated gases and the addition of O_2 and/or H_2. For a recent review of SiC RIE see reference [1]. The main goal of current SiC etching research is to increase the etch rate, to produce suitably high anisotropic profiles, while at the same time to minimize etching residues and damage. To reach this goal, one approach has been to shift to the use of high density plasma sources, such as electron cyclotron resonance (ECR) sources or inductively coupled (ICP) plasmas. While these etching systems are more complex and more expensive than RIE systems, the use of ECR has resulted in increased etch rates, which broke through the 100 nm/min level [2]. However, it has also been reported by Flemish and Xie [3] that in order to obtain high anisotropy in ECR etching, one had to operate under conditions which reduce the etch rate by nearly a factor of 10. An alternative approach is to develop RIE etching conditions specifically designed for high etch rate. This has been generally accomplished by increasing the plasma pressure and RF power. For example, Wolf and Helbig [4] have reported etch rates as high as 300nm/min at 300W in a SF_6/O_2 plasma operated at 190 mTorr. Casady et *al.* [5] have utilized NF_3 at high pressure (100-300 mTorr), high flow rate (95-110 sccm) and high power density (~1.5-2.5W/cm^2) to obtain etch rates from 120 to 180 nm/min.

In this paper we report on experiments designed to optimize the SiC etch rate in pure NF_3 under conditions easily achievable with conventional RIE equipment: plasma pressure less than 100 mTorr and gas flow rate under 100 sccm. The etching was carried out in a Plasma Therm PK 1441 reactor. To prevent residue formation [6] due to the "micro-masking" effect from the Al electrode, a graphite sheet was utilized as a cover. This technique was previously shown [7] to be very effective in SiC RIE in various fluorinated plasmas. We explored the following etching parameters: (a) flow rate - from 20 to 120 sccm; (b) pressure - from 50 to 100 mTorr; (c) RF power - from 200 to 300W. Given our electrode size of ~500cm^2, the power density ranged from 0.4 to 0.6 W/cm^2.

In our experiments we have utilized "research" grade 4H and 6H SiC substrates from Cree Research Corp. Substrates of both polytypes were oriented 3.5° off the c-axis and were doped n-type with a carrier concentration of ~ 1×10^{18} /cm^3. The surface used for etching was the as-received, polished Si-face. No epitaxial layer was present on the substrate, nor was any surface preparation or treatment used other than routine chemical cleaning. A thin film Al mask of 3000Å was deposited using a lift-off process. Unless otherwise mentioned the etching experiments were carried out for a duration of 5 min.

2. Results and Discussion

In this section we present and discuss results on NF_3 etching on 4H and 6H SiC samples. The etch rates are shown in Fig. 1 as a function of NF_3 flow rate, along with the corresponding values of DC bias. These experiments were performed at 80 mTorr and 300W RF power.

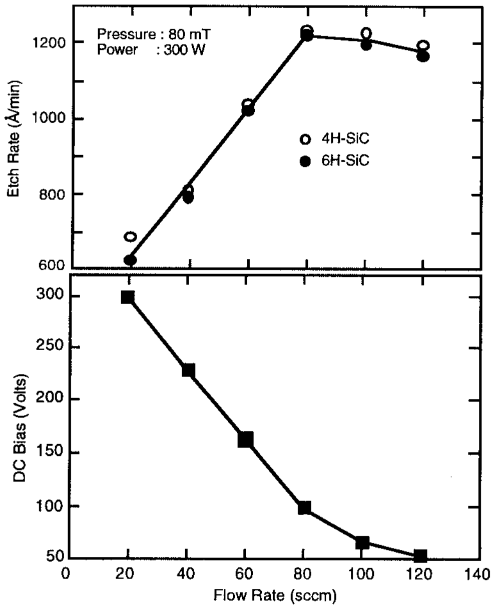

Fig. 1 Etch rate and DC bias vs. NF_3 flow rate.

Very similar values of etch rate for the 4H and 6H polytypes were observed in most cases. A linear increase in etch rate from ~ 650-700 to ~ 1200 Å/min is observed as flow rate values increase from 20 to 80 sccm. This is accompanied by a monotonic decrease in the DC bias from 300 to 100 V. Increasing the flow rate generates an increase in ion flux. This, in turn, reduces the net charge built up on the sample and the related self-induced DC bias. These observations indicate that in this regime the etching process is reactant-rate-limited.

Increasing the NF_3 flow rate beyond 80sccm actually results in a slight decreasing trend in etch rate for both polytypes. This is accompanied by a much lower rate of decrease in DC bias.

It appears that for 300 W of RF power (equivalent to $0.6W/cm^2$) in our system, a DC bias of ~100V represents the so-called cross-over bias [8] between reactant-rate-controlled etching and bias-controlled etching. At flow rates in the 20 - 80 sccm range, the self-induced bias is sufficiently high so that the etch rate is determined by the arrival rate of reactants. Increasing the flow rate above 80 sccm, results in a reduction of the DC bias below the apparent 100 V threshold for the bias-controlled regime where the etch rate is affected by the energy with which the ions bombard the sample surface.

It is important to point out that at the flow rate of 120 sccm, the average etch rate of the two SiC polytypes is only slightly below 1200Å/min, while the DC bias is only ~50V. This is quite important for SiC device fabrication, as the low bias should greatly reduce RIE-induced damage.

The effect of NF_3 plasma pressure on the SiC etch rate is shown in Fig. 2 at the same power of 300W. We have utilized a flow rate of 80 sccm, which was determined to provide the highest etch rate in the flow rate experiments (see Fig. 1). It is observed that increasing the pressure from 50 to 80 mTorr results in a monotonic increase in etch rate from ~850 Å/min to ~1250 Å/min. In general, as the pressure is increased, the mean free path of the plasma components decreases, leading to increasing collisions between electrons and gas molecules. This produces an increasing density of reactant species which can remove material at a faster rate. At the same time, the ion flux also

Published in 'Silicon Carbide, III-Nitrides and Related Materials', Year: 1998, pp: 829-832
Periodical: Materials Science Forum Vols. 264-268
Published on http://www.scientific.net, eMail: office@scientific.net

increases and this reduces the DC bias and the effectiveness of physical etching. As in the case of varying the flow rate, when the pressure is increased beyond a certain level (80 mTorr), a decrease in etch rate is observed. This occurs at the same value of the DC bias (100V), indicating the same shift between reaction-rate-controlled etching and bias-controlled etching.

Finally, the effect of varying the RF power on the SiC etch rate is shown in Fig. 3. In this case the NF_3 flow rate and plasma pressure were fixed at 80 sccm and 80 mTorr, respectively. It is observed that the etch rate increases monotonically with RF power, from 900 Å/min at 200W to 1250 Å/min at 300W. As the power input to the plasma is increased, the density of particles in the plasma increases due to more effective ionization and dissociation. This means that more electrons, neutrals and ions (striking the surface at an increasing energy) are incident at the surface of the wafer being etched thereby combining to produce a higher etch rate.

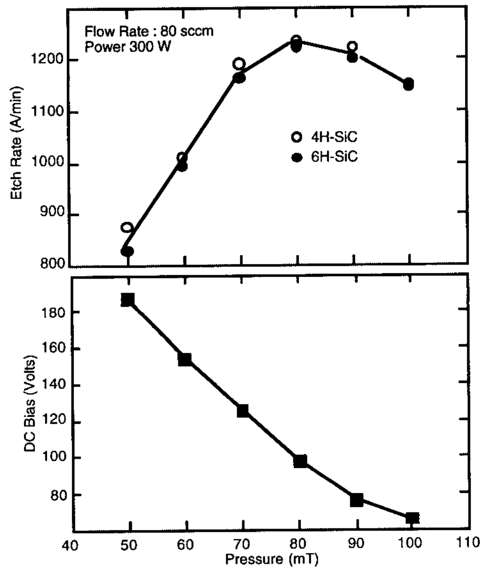

Fig. 2 Etch rate and DC bias vs. plasma pressure.

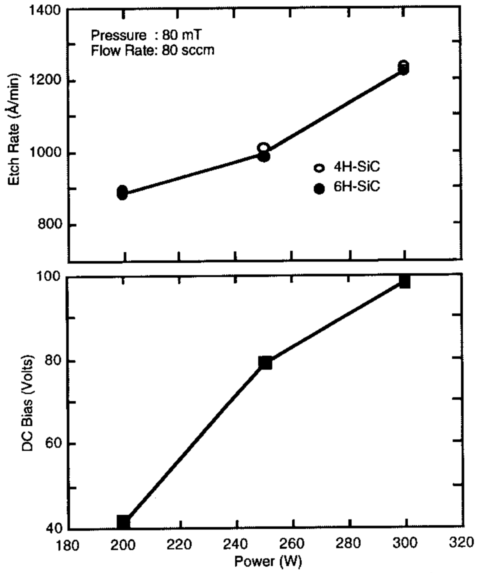

Fig. 3 Etch rate and DC bias vs. plasma power.

SEM microphotographs of the 4H SiC samples etched at 80 mTorr and 300W with 80 sccm of NF_3 are shown in Fig. 4. No residues are observed in either the etch field or on the Al mask field. Indeed, no residues were observed under any of the etching conditions utilized with either 4H or 6H SiC samples. The step edge appears nearly vertical, indicating a surprisingly high anisotropy under these etching conditions.

AFM was utilized to measure the surface roughness of the etch field. The average surface roughness (R_a) of a 4H sample etched for 10min under the optimum conditions of 80sccm, 80 mTorr and 300W was approximately 2.9Å. This represents only a very small increase from the surface roughness of the as-received SiC surface of 2.7Å. It is interesting to mention that we have evaluated the roughness of SiC "production" quality epitaxial layer samples and found them to be significantly smoother, with an R_a of 1.8Å.

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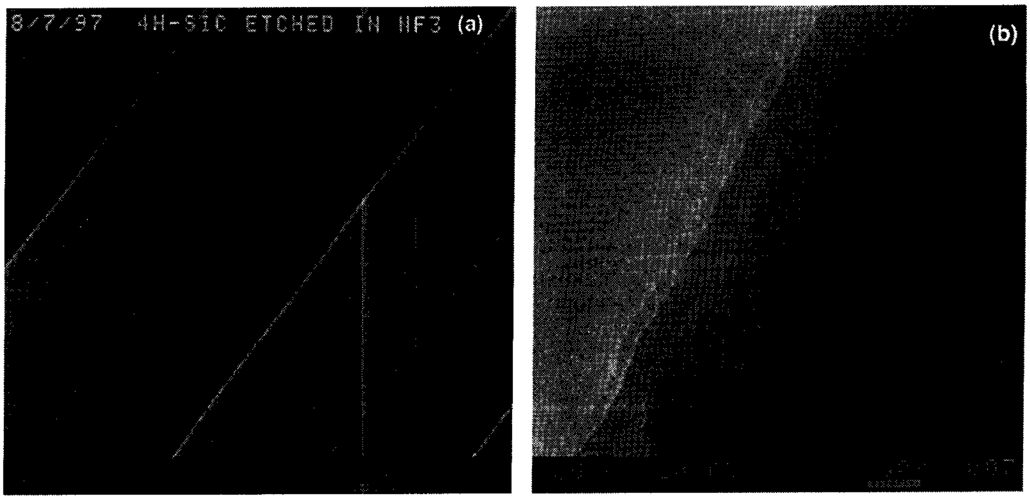

Fig. 4 Patterns etched in 4H-SiC at 80 mTorr with 80 sccm of NF_3:
(a) 5 min - 10kx magnification.; (b) 10 min - 20kx magnification.

3. Summary

The process conditions including the flow rate, pressure, and RF power for reactive ion etching of SiC in NF_3 plasma have been investigated. Anisotropic, residue-free etching has been obtained with relatively high etch rates. The effect of etching on surface morphology under high etch rate conditions has been evaluated by AFM. The etched regions have been found to be very smooth, possibly due to lower ion bombardment energies at higher pressures. Etch rates as high as 1200 Å/min have been obtained for both 6H and 4H SiC polytypes.

Acknowledgments

The authors are pleased to acknowledge many useful discussions with J. Scofield and the support of the USAF Wright Laboratory / Propulsion Directorate and of the Ohio Aerospace Institute.

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