Si/SiO_2 etch properties using CF_4 and CHF_3 in radio frequency cylindrical magnetron discharges

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Si/SiO_2 etch properties have been studied in CF_4 and CHF_3 cylindrical magnetron rf discharges as a function of magnetic field strength. As the magnetic field strength increases from 0 to 250 G, radical densities continuously increase and dc bias voltages exponentially decrease. The maximum etch rates of Si and SiO_2, however, occur at an intermediate value of magnetic field strength which corresponds to the self-bias voltage being between 25 and 50 V. Using magnetic field strengths near the maximum etch rate, we obtained vertical features having < 2000 Å widths and trenches deeper than 2 μm. Etch rates exceeding 2500 Å/min were obtained in a CF_4 plasma, with little or no radiation damage, and with minimum contamination of the surface.

As the dimensions of devices in very large scale integrated circuits (VLSICs) decrease, the use of reactive ion etching (RIE) to fabricate structures becomes an increasingly more important technology.[1] Also, as the size of the Si wafers increases, single-wafer processing becomes a more attractive method of fabrication compared to batch processing.[2] High etch rates, however, are required to obtain a similar throughput as batch processing. In spite of the fact that the rate of RIE is usually much slower than that of plasma etching, reactive ion etching is currently the process of choice for single-wafer systems. RIE, however, often produces unwanted radiation damage and/or contamination of the surface which must be subsequently removed. Processing methods having higher etch rates and less damage are therefore required. Electron cyclotron resonance (ECR) plasma etching is one such method which may meet these requirements.[3]

Magnetron reactive ion etching is also an attractive technology for VLSIC single-wafer processing due to the high etch rates and small ion bombardment energies one can obtain compared to RIE.[7-12] The lower ion energies cause less damage and reduce the need for annealing of radiation damage after etching. The high etch rates are due to confinement of the plasma by the applied magnetic field.In a previous study[13] using a cylindrical magnetron rf discharge we showed that the etch rates generally increase with increasing magnetic field strength; however, there was an optimum magnetic field above which etch rates decreased. In this letter, we further report on the etch properties of Si/SiO_2 obtained in CF_4 and CHF_3 cylindrical magnetron radio frequency (rf) discharges. We show that this method is a viable technology for VLSIC fabrication and present submicron Si etch profiles as a function of magnetic field strength as a demonstration.

The experimental system used in this study is described in detail elsewhere.[14] The B field was generated by electromagnets which were supported by carbon steel to improve the uniformity of the field. The cylindrical chamber was made of stainless steel. The inner cylindrical post, serving as the powered electrode (13.56 MHz), was made of anodized aluminum, was water cooled, and had flattened surfaces to mount wafers. An electrostatic probe was used to measure ion densities. The specimens used in the experiment were (100) n-type Si and SiO_2 prepared by wet oxidation. To study etch rates, samples were partially patterned with photoresist (Shipley 1350J). To study etch profiles of Si/SiO_2, Cr masks were prepared by both optical and electron beam lithography using a lift-off process. Using optical lithography, the linewidths were 2 and 4 μm, while using electron beam lithography, the linewidths were 0.2–0.5 μm.

Optical emission spectra were measured for CF_4 and CHF_3 discharges (0.45 W/cm^2 at 3 mTorr) as a function of magnetic field strength. Using Ar actinometry, the emission intensities[15] of atomic F (703.7 nm) were normalized by the intensity of Ar at 750.4 nm (which was added to a mole fraction of 4%) to estimate F atom densities, as shown in Fig. 1. F atom densities increased with increasing magnetic field strength. The F atom densities in CHF_3 plasmas were less than using CF_4 as one would expect in analogy to CF_4/H_2 mixtures.[13] The ion densities in the CF_4 plasma increased almost linearly with increasing magnetic field strength while the bias voltages decreased exponentially (see Fig. 1). The

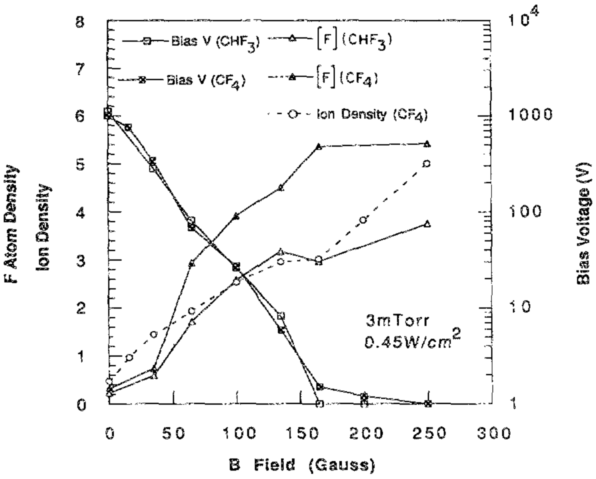

FIG. 1. Relative F atom densities estimated from Ar actinometry and dc bias voltage for CF_4 and CHF_3 plasmas (3 mTorr, 0.45 W/cm^2) as a function of applied magnetic field strength. As a reference, ion densities for the CF_4 plasma for the same conditions are also shown.

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bias voltages also decreased with increasing power deposition.

Etch rates of Si and SiO_2 using CF_4 and CHF_3 are shown in Fig. 2 as a function of magnetic field strength for the same conditions as Fig. 1. The maximum etch rates are obtained at an intermediate value of magnetic field which does not correspond to the maximum radical density. The magnetic field at the maximum etch rate increased with increasing discharge power. The etch rates in CHF_3 plasmas have the same trends as with the CF_4 plasmas. However, the selectivity of SiO_2 over Si increased to 6 using CHF_3 compared to using CF_4 at the same power density and pressure. The increased selectivity appears to result from an increase in polymer deposition on the Si, as measured from cross-sectional views of the samples obtained using transmission electron microscopy. For typical discharge conditions (100 G, 3 mTorr, and 0.75 W/cm^2), the thickness of the polymer layer on etched Si increased from 2.5 nm in a CF_4 plasma to 5.5 nm in a CHF_3 plasma.

The dependence of Si/SiO_2 etch rates on applied magnetic field can be explained by the combined effects of increasing radical density and decreasing bias voltage.[13] The increase in the densities of CF_3 and F radicals, and of ions with the magnetic field increases the chemical components of the etch rates. The increase is sustained until the lower energy of ion bombardment resulting from the decrease in the dc self-bias is insufficient to activate the etching process. Below this critical ion energy (i.e., at higher B fields), etch rates decrease. Therefore, there is a maximum in the etch rates where the two effects are compensating. The maxima in etch rates at intermediate values of magnetic field have also been observed by Lin I *et al.*, although not by others.[7,9] The precise value of the B field at which the maximum in etch rate occurs depends on system parameters. For example, operating with larger electrode area ratios results in larger dc biases. The critical ion energy is therefore obtained at higher B fields where the plasma density is also higher. One would therefore expect the maximum etch rate to be both larger and occur at higher values of magnetic field in more asymmetric systems.

Our previous study of the etch profiles of Si and SiO_2 (Cr mask, 2 μm lines) showed that the etch profiles changed from tapered to reentrant as the magnetic field increased from 0 to 250 G. Vertical etch profiles were obtained at an intermediate magnetic field strength which corresponded to the highest etch rate. The rate of erosion of the mask increased with decreasing magnetic field strength and increasing ion energies. The degree of the reentrant etch profiles was smaller for Si etching than for SiO_2 etching.

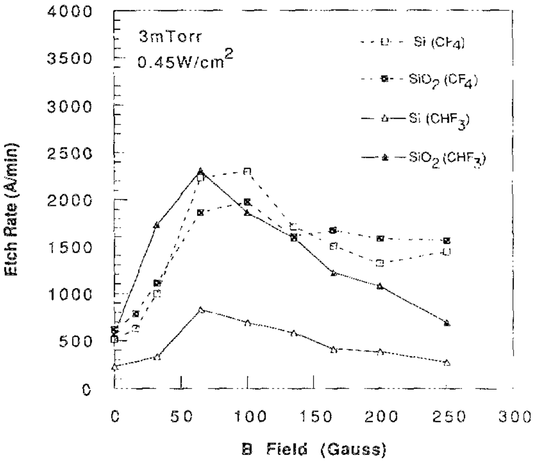

FIG. 2. Etch rates of Si and SiO_2 in CF_4 and CHF_3 plasmas (3 mTorr, 0.45 W/cm^2) as a function of magnetic field strength.

Si etching at conditions near those yielding vertical etch profiles were studied with finer resolution using electron beam lithography to generate Cr masks having 0.2–0.5 μm

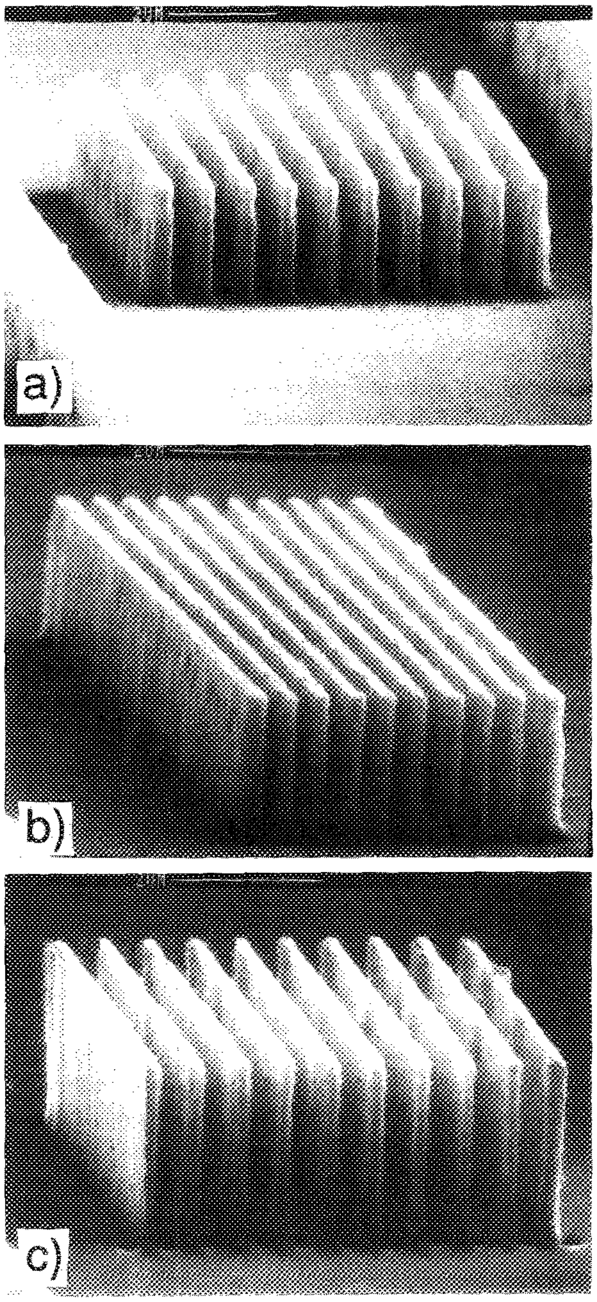

FIG. 3. Etch profiles of Si obtained in 3 mTorr CF_4 plasmas at 0.45 W/cm^2 as shown by SEM. The horizontal scale line at the top of each figure is 2 μm in length. The specimens were exposed to the processing plasma until about 2 μm of Si was etched away. The magnetic fields and dc bias voltages are (a) 65 G, 100 V; (b) 100 G, 35 V; and (c) 165 G, a few V. The etch rates are (a) 2000 Å/min, (b) 2500 Å/min, and (c) 1800 Å/min. The irregular shapes of the side etch profiles shown in (a) and (b) resulted from the original mask and not from an intrinsic property of the etching.

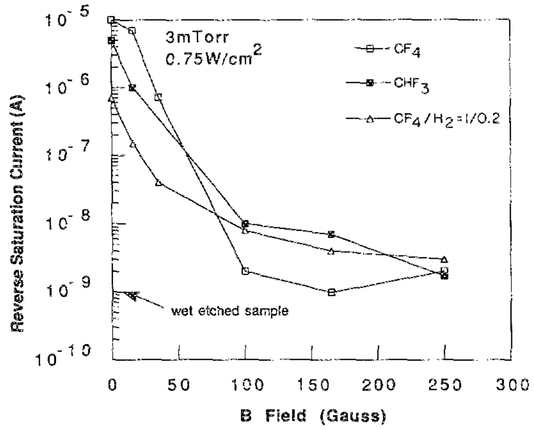

FIG. 4. Reverse saturation current (leakage current) of Schottky diodes made from blank etched Si for various gas mixtures as a function of magnetic field strength. The specimens were exposed to the processing plasma until about 2 μm of Si was etched away. 10^{-9} A is the leakage current for a wet-etched sample.

lines. The discharge conditions were 3 mTorr of CF_4 and a power deposition of 0.45 W/cm^2. Si was etched about 2 μm deep using different magnetic field strengths and the results are shown in Fig. 3. The Si etch profiles shown in Fig. 3(a) were obtained using a mask with 0.4 μm lines with $B = 65$ G. The bias voltage was almost 100 V and the etch rate was close to 2000 Å/min. The etch profile had a somewhat tapered shape most likely originating from erosion of the mask. The irregularity of the side etch resulted from the irregular shape of the original mask and not from an intrinsic property of the etching. The fact that the etching process reproduced these irregularities (dimensions $\leqslant 100$ nm), shows that the resolution of the etch is limited by the mask. Etch profiles having more vertical walls were obtained at $B = 100$ G (0.2 μm mask lines), which corresponded to the maximum etch rate [Fig. 3(b)]. The bias voltage was about 35 V and the etch rate was ≈ 2500 Å/min. Nearly vertical etch profiles were obtained at $B = 165$ G as shown in Fig. 3(c). The etch rate was lower, ≈ 1800 Å/min, and the bias voltage was only a few volts. In this case, the side etch was smooth due to improved masking.

To study radiation damage, Schottky diodes were made from the etched Si samples and the reverse bias leakage currents were measured[17,18] (HP4145A semiconductor parameter analyzer) as shown in Fig. 4. The samples were etched without masks until 2 μm of Si was etched away in 3 mTorr CF_4, CHF_3, and $CF_4 + 20\%\ H_2$ plasmas at a power deposition of 0.75 W/cm^2. The degree of radiation damage was correlated with the magnitude of diode leakage current and decreases with increasing B field. The leakage currents of the samples etched at magnetic fields higher than that for the maximum etch rate were close to the value obtained with wet etching, and therefore indicated negligible damage. The degree of surface contamination shown by secondary-ion mass spectroscopy was also lower at higher magnetic field strengths. The low radiation damage and low contamination at high magnetic strengths are due to the combined effects of low ion energy bombardment and high ion/radical densities. The low ion energy bombardment reduced the depth of the damaged layer while high ion/radical densities in the plasma removed surface contamination quickly.

In summary, we studied Si etch profiles as a function of magnetic field strength in cylindrical magnetron discharges. We obtained highly anisotropic etch profiles for conditions near those for the maximum etch rate. Line profiles < 2000 Å/min and etch rates > 2500 Å/min were demonstrated. The etch resolution appeared to be limited by the mask. At these conditions little, if any, radiation damage was observed and the surface contamination was minimum.

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