Relative fluorine concentrations in radio frequency/electron cyclotron resonance hybrid glow discharges

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The relative concentration of atomic fluorine was measured in a radio frequency (rf) glow discharge and a modified electron cyclotron resonance microwave/rf hybrid discharge in CF_4 using an actinometric technique. The dependence of fluorine concentration on rf and microwave power, pressure, flow, and excitation source are presented. Anomalous behavior with rf power at constant microwave power was observed when using the Ar 750-nm line as the actinometric species.

Combining a microwave source with a radio frequency (rf) system provides a means to independently control radical species production and ion bombardment energy. Conventional rf discharge reactors perform both tasks necessary for anisotropic etching, but in an interdependent fashion: (1) dissociation of feed gas into reactive radical constituents and (2) acceleration of ions onto the wafer surface. On the other hand, microwave electron cyclotron resonance (ECR) discharges are much more efficient at gas dissociation, but require elaborate magnetic confinement and/or biased ion extraction grids to produce directed ion streams. In a combined, or hybrid, system the microwave discharge region acts as the reactive species source and the rf discharge establishes the self-induced dc bias on the wafer chuck for ion acceleration. This arrangement is preferred over having biased ion extraction grids downstream of the ECR source which can contaminate the system.

To study the performance of the hybrid system, relative concentration trends of atomic F were measured in an rf glow discharge and a modified ECR/rf hybrid discharge in CF_4 using the actinometric technique. This optical technique provides the relative concentration of reactive species. It was first introduced to study CF_4 and CF_4/O_2 rf glow discharges[1,2] and the specific application used here is outlined in Ref. 3. The dependence of F concentration on rf and microwave power, pressure, flow, excitation source, and microwave cavity length was determined in both a pure rf and a hybrid system. The parameter space of interest was 3–20 sccm CF_4, 8.5–45 mTorr, 20–400 W rf power, and 200–600 W microwave power. The F trends in the hybrid system are compared with preliminary silicon etching results.

The experiments for this study were conducted on two systems. The first was a commercial 13.56-MHz rf parallel-plate radial flow reactive-ion etcher (RIE), a SEMI Group 1000 TP/CC. The second system is similar to the first system, except the showerhead upper electrode was replaced with a Wavemat ECR, MPDR 325. The source consisted of a 23-cm-diam quartz disk with a gas ring at the base and a 37-cm-diam, adjustable length resonant cavity. Using a 2.45-GHz microwave power supply, multimode excitation is expected for this cavity.[4] Twelve rare-earth magnets surrounded the discharge in an alternating pole configuration producing multipolar ECR zones. The etch gases were fed into the chamber through a distribution ring between the cavity base and the top of the chamber walls. The system was pumped with a Roots blower backed by a mechanical pump. This pumping package limited the processing pressure to be >8 mTorr. Details of the experiment can be found in Refs. 5 and 6.

The actinometric technique allows the relative concentration of ground-state atomic species to be determined under certain conditions independent of changes in the electron density and energy distribution function. This is achieved by introducing a small amount of an inert gas as an actinometer to which the reactive species emission is referenced. The specific requirements for the validity of this technique are as follows: (1) the emission from the two species must arise from deexcitation of higher-level states which are similar in energy; (2) the higher-energy states are created by direct electron impact excitation of ground-state atoms; and (3) the electron impact excitation cross sections are similar in shape and threshold energy. In this investigation, the actinometer was Ar (750 and 703 nm) and the reactive species was F (704 nm). To minimize plasma perturbation from the addition of the actinometric gas, the argon flow rate was maintained at 5% of the CF_4 flow. The emission signals were collected via an optical fiber. In the RIE system, emission was collected through a small window about 4 cm above the electrode. In the hybrid system emission was collected in two positions, through a quartz window on the side of the chamber 2 cm above the bottom electrode and through a viewing port on the microwave cavity which gave access to the quartz ECR containment disk.

Both the F and Ar emission, and hence the F concentration, changed as a function of cavity length and typically increased with decreasing cavity length. The variation of F concentration with residence time was examined by

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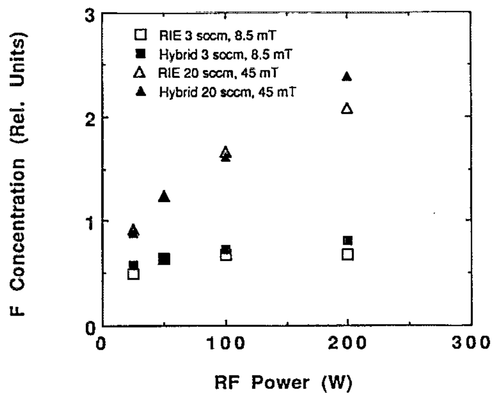

FIG. 1. F concentration as a function of rf power in both the RIE (open symbols) and the ECR/rf hybrid (closed symbol) systems for two cases, (□) 3 sccm and 8.5 mT and (△) 20 sccm and 45 mT. Note there was no application of microwave power in the ECR/rf hybrid.

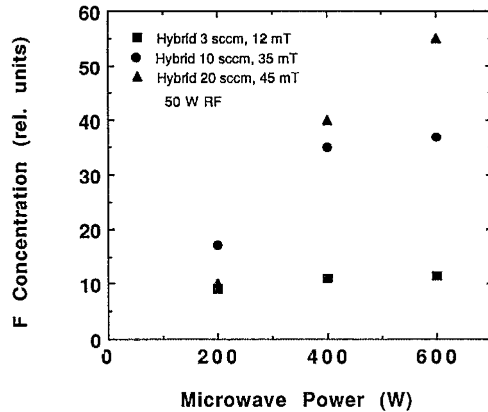

FIG. 2. F concentration as a function of microwave power in the ECR/rf system at (■) 3 sccm and 12 mT, (●) 10 sccm and 35 mT, and (▲) 20 sccm and 45 mT with 50 W rf power.

varying the pressure and flow rate. The F concentration was expected to decrease with increasing flow or decreasing pressure since the residence time is less as has been observed by mass spectrometry measurements.[7] As expected, the F concentration in the ECR/rf system decreased substantially for increased CF_4 flow and increased with pressure in both the ECR/rf and RIE systems. In the RIE, at low pressure, the F concentration remained approximately constant and at higher pressure the F concentration decreased with increasing flow. The residence time effect did not change the F concentration greatly in the RIE due to the low overall F production rate and the chamber loading effects which become important at low concentrations.[3]

In the RIE, the F concentration increased with rf power as expected. To determine the effect of replacing the upper electrode with the ECR source, the F concentration was monitored as a function of rf power at the same conditions as the RIE. Even though the two reactors have very different geometries, the trends and magnitudes were approximately the same (see Fig. 1).

When microwave power was added to the hybrid system in addition to 50 W rf power, the F concentration increased substantially (see Fig. 2). Note the relative magnitude of the fluorine concentration can be an order of magnitude or more higher for the rf plus microwave power (Fig. 2) compared to the rf alone (Fig. 1). As the microwave power was increased, the F concentration also increased as expected.

An anomalous behavior was observed when the rf power was varied in the hybrid system. With a constant microwave power of 200 W, the atomic F concentration (i.e., the ratio of F 704 nm to Ar 750 nm) decreased with increasing rf power as shown in Fig. 3. This trend was also observed at higher microwave powers (250 and 400 W), three CF_4 flows (3, 10, and 20 sccm), and 20–45 mTorr. Collecting the emission data directly from a viewport on the side of the microwave cavity also produced similar results. The same trend was observed with an Al electrode as well as a quartz-covered electrode. Note, however, that Si etch rates, which tend to follow the F concentration, increased with increasing rf power under these operating conditions.

Increasing the rf power did increase the F emission intensity as well as the Ar emission intensity. The ratio, however, decreased due to the larger rate of increase of the argon emission intensity relative to the F emission intensity. This effect may be due to the different excitation threshold energies of the lines. The F 704-nm line has a threshold energy of 14.79 eV compared to 13.52 eV for the Ar 750-nm line. If the electron energies increase with increasing rf power, an enhancement in the population of the species with lower excitation thresholds can occur, depending upon the shape of the electron energy distribution function and the separation of the threshold energies.

Langmuir probe measurements[8] indicate that the electron energy distribution function may be approximately Maxwellian in some ECR systems which may or may not apply here. We were not able to verify this assumption since a Langmuir probe was not available for this experiment, however, the electronic temperature of argon, which

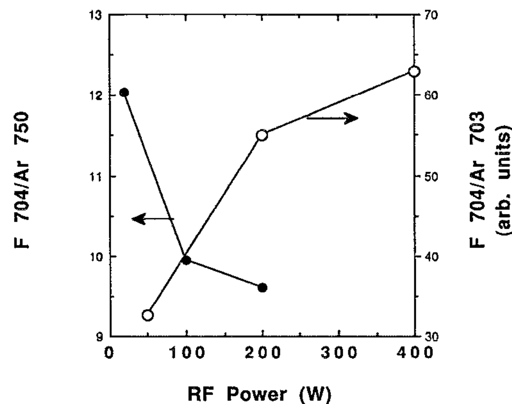

FIG. 3. F concentration as a function of rf power in the ECR/rf system. The left-hand axis is the relative concentration obtained from F 704 nm/Ar 750 nm and the right-hand axis is the relative concentration obtained from F 704 nm/Ar 703 nm for 20 sccm of CF_4, 45 mT, and 200 W of microwave power.

assumes a Maxwellian distribution, could be estimated from atomic Boltzmann plots[9] of the intensities of Ar lines (706.7, 750.4, and 751.5 nm). The electronic temperature of Ar was found to increase from 7800 to 9200 K as the rf power was increased from 20 to 200 W at 20 sccm CF_4 and 45 mTorr. This may indicate an increase in the average electron energy which increases the excitation of the Ar 750-nm line (at 13.52 eV) preferentially over the higher-energy F 704-nm line (at 14.79 eV).

The Ar 703-nm line at 14.88 eV has a similar excitation threshold to the F 704-nm line but was very difficult to use because of its low intensity and interference from the CF_x continuum emission and the nearby, intense F 704-nm line. However, for cases where the signal-to-noise was acceptable and when the continuum emission was subtracted from the Ar 703-nm line, the resulting F concentration trends increased as expected with increasing rf power, as shown in Fig. 3.

In the hybrid ECR/rf system, the actinometric results showed an increase in the F concentration as the microwave power and pressure were increased, which corresponds to an increase in Si etch rates. The Si etch rate also increased with rf power. The etch profiles indicated significant chemical etching as they were somewhat isotropic. Compared to etching in the RIE, higher Si etch rates were obtained in the hybrid ECR/rf system, which is in agreement with the actinometry results.

As described above, the ECR/rf system operates well in the traditional parameter range of the RIE. The hybrid system offers more flexibility and controllability than the RIE because it has a larger dynamic range of operating parameters and because it has the ability to independently adjust the reactive component using the ECR source and ion bombardment component using rf biasing. More work needs to be done, however, to assess the advantages for selectivity, damage, profile control, and uniformity.

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