REACTIVE ION ETCHING FOR PATTERNING HIGH ASPECT RATIO AND NANOSCALE FEATURES

M. Avram, A. Avram, F. Comanescu, A. M. Popescu, C. Voitincu

National Institute for Research and Development in Microtechnologies, Romania, Bucharest
E-mail: marioara.avram@imt.ro

Abstract–*This paper presents the authors' understanding of the mechanistic aspects of the role of energetic ion bombardment in low density plasma reactive ion etching (RIE). The phenomenon of ion assisted gas surface chemistry is described and the importance of this phenomenon in obtaining anisotropic is emphasized. It was studied the dependence of etching rate of RF power and pressure in reactor. RF power and pressure in the reactor has significant effect not only on the etching rate, but also on the degree of anisotropy and etching profiles for various RF power and pressure in the reactor.*

Keywords: *reactive ion etching, nanoscale patterning.*

1. INTRODUCTION

Plasma etching is the process by which micron and submicron geometries are made for microelectronic devices and MEMS. At low pressures (less than 100 mTorr), in the area of radiofrequency discharges, the gases that contain fluoride dissociate into neutral and ionic radicals. These radicals diffuse or they are accelerated to the surface of the wafers where they are being absorbed. Dry etching can be described simply as a method by which the substrate surface is etched by the ion bombardment or by chemical reactions between reactive species in plasma and the surface or some combination of these two processes. Transfer of relief in the substrate in micron and submicron domain requires a technique that is able to transfer a high-resolution relief from the photoresist to the substrate. To obtain micron or submicron resolution of etched structures, underetching must be minimized or very well controlled. The minimum underetching assisted by plasma is obtained in general at low pressure where the physical effects due to vertical direction of ions play an important role. But on the other hand, controlled underetching can be used to obtain tilted reliefs. Underetching may be modified by changing the relative contribution of physical and chemical effects. Very important for most applications is that the material to be etched is engraved with a rate much higher than the mask or substrate, so the etching process has a high selectivity. The selectivity can be improved if the etching is not based on physical effects, but is assisted by the processes of chemical species generated in the plasma and the substrate surface. Dry etching in a RIE system is due to combinations of physical and chemical effects [1]. The selectivity of reactive ion etching can be optimized through a convenient choice of etch configuration, gas composition, pressure and flow rate. Selectivity is usually much better at high pressures to which etching is due to much more to chemical effects than the physical effects.

2. PLASMA DILUTION EFFECT

In dry etching, adding a very small quantity of gas can significantly change the etch rate by modifying the activation energy of the reaction. More precisely, adding a very small quantity of gas changes the course of the reaction and induces a reaction that requires small activation energy. The added gas can increase the etching rate. Adding O_2 to SF_6 or CF_4 when etching Si, or adding H_2 to CF_4 when etching SiO_2 are just a couple of simple such examples. When adding H_2 to CF_4 or C_2F_6 plasmas, the reactions become more and more complex. In the case of C_mF_n/H_2, the reactions CF_3 and F with H_2 and H for making HF and CF_3H are dominant neutral reactions. All these reactions increase the proportion of the radicals C/F. The most important events are the dissociation and ionization of H_2 and the dissociation of CHF_3. CHF_3 represents a minor species, when compared to HF. Making CHF_3 can be a „tank" for the CF_3 radicals which link the absorbable species. Anyway, the reactions have high rates [1].

$$CHF_3 + F \rightarrow CF_4 + H \qquad (1)$$

$$CHF_3 + F \rightarrow CF_3 + HF \qquad (2)$$

The energy of the CF_3-H link, of 4,6eV, is not very high, so the impact-electron dissociation can occur. Within the plasma, the CHF_3 concentration is not expected to be high. Adding H_2 permits the

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absorption of the hydrogen atoms on the surface and the HF desorption. The effect of adding O_2 to CF_4 or C_2F_6 leads to more than one interpretation. Adding O_2 leads to an increase in etching rate of the Si, as well as to the fluorescence of the F excited atoms. This suggests a decrease in the C/F proportion by increasing the F atom density. The O atoms can be absorbed at the surface where they can link to the C atoms, also absorbed. Desorption occurs as CO. The most likely mechanism supposes the appearance of the intermediary species that produce the F atoms. Adding O_2 changes the electron energy distribution for low energies [2, 3].

Thus, the concentrations of the F ions is influenced by oxygen: (1) oxygen delays the F atoms' recombination with other species, either by reacting with them or by blocking the access to a favorable recombining surface; (2) oxygen causes decrease rate of reaction of F atoms with Si and ions of other species by oxidizing them; (3) oxygen reacts with species containing F, releasing F atoms. The reaction may take place on the surface or during a gas phase. Among the functions of O_2: (1) it stops the surface reaction which might be favorable to low pressure recombining; (2) the reaction of oxygen with unwanted films, accumulated on the surface of the substrate, creating volatile products: CO, CO_2 and COF_2. The dissociation rate of CF_4 is an electron energy function and it can be higher in the pure CF_4 discharge area [3].

The silicon etching rate can be increased by adding small amounts of argon in plasma of SF_6. The silicon etching rate relatively low by molecule F_2 is due to the small probability of absorption of fluorine molecules on silicon. Bombardment with Ar^+ ions increases this probability as a result of two possibilities: (1) bombardment with Ar^+ ions to generate a high density of sites capable to absorb fluorine chemical molecules; (2) bombardment with Ar^+ ion molecule causes dissociation of fluorine through direct molecular fluorine so that will be adsorbed on the surface in a molecular state with relatively weak chemical links.

The second mechanism cannot be applied to discharge in CF_4 because fluorine atoms and molecules F_2 are not active dominant species in this case.

3. EXPERIMENTAL SET-UP

Silicon wafers were washed in H_2SO_4+HNO_3 and then deionized water and a dip in HF 10%. These silicon wafers were divided into 4 groups: A, B, C and D. On wafers in group A was deposited silicon nitride on wafers in group B was grown thermal oxide, those of group C pyrolytic oxide (CVD). All wafers of the 4 groups were patterned with a mask with squares of 4×4mm. Was etched Si_3N_4 in CF_4 plasma in steps of 30 seconds and after etch silicon nitride thickness was measured in 5 points from the wafers using elipsometer. Etching was done varying RF power and maintaining the same flow of plasma composition. Then remained constant RF power and was varied flow of the gas. The effect of O_2, CHF_3 or CF_4 addition to SF6 was studied. SiO_2 was etched by CHF_3 plasma in steps of 1 minute and was studied the etching rate dependency of RF power, flow rate of CHF_3 and percentage of O_2 added to the CHF_3. Silicon was etched in SF_6 plasma in steps of 1 minute and depth has been measured with the profile-meter. It was studied the etching rate dependency of RF power, the flow rate of SF_6 and percentage of O_2 added to the SF_6.

4. EXPERIMENTAL RESULTS

In Table 1 is shown the silicon etching rate according to the RF power and flow rate of SF_6 with 12% O_2.

Table 1. Silicon etching rate [nm/min]

Power[W] Flow [sccm]	100	150	200	250
40	150	250	900	2125
50	160	280	950	2550
60	180	300	1000	2800

In Table 2 is shown the silicon etching selectivity towards SiO_2 (ratio of etching rate of Si to etching rate of SiO_2) function of RF power and flow rate of SF_6.

Table 2. Silicon etching selectivity

Power[W] Flow [sccm]	100	150	200	250
40	50	40	30	20
50	60	42	35	22
60	60	45	40	25

In Table 3 is shown the influence of SF_6 plasma dilution with O_2 towards silicon etching rate and selectivity. RF power was 200 W.

Table 3. Silicon etching rate and selectivity

SF_6:O_2	10:3	8:3	6:3	4:3	2:3
Etching rate [nm/min]	900	700	500	80	50
Selectivity (Si/SiO_2)	30	20	15	3	2

In Table 4 is shown the silicon nitride etching rate according to the RF power and flow rate of CF_4 with 4% O_2.

Table 4. Silicon nitride etching rate [nm/min]

Power[W]	100	150	200	250
Flow [sccm]				
30	40	65	90	140
35	38	70	60	120
40	30	50	80	120

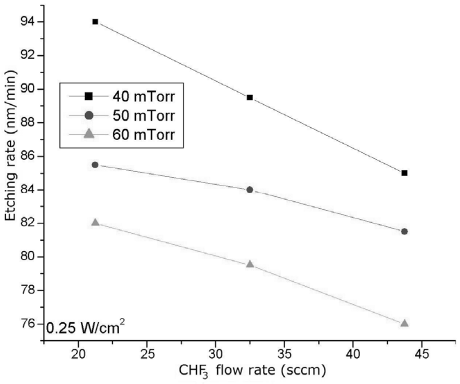

Fig. 1. SiO_2 etching rate dependency of pressure and CHF_3 flow rate. RF power 100W.

The selectivity of silicon etching towards SiO_2 decreases with increasing dilution. The figure 1 gives the dependency of etching rates of SiO_2 in CHF_3/O_2, power density of 0.25 W/cm^2 versus CHF_3 flow rate and the pressure in reactor.

A tilted profile can be obtained in SiO_2 by etching in the CHF_3 plasma with O_2. Etching rate decreased with the flow of CHF_3 assigned relative earnings polymerization across the etching at constant power density.

Compared to the CF_4 plasma, the amount of free F atoms seem to be much higher and the etching is isotropic. To control underetching, dilute SF_6 with a non-reactive gas, such as argon. The reagent gas dilution increases with both decrease of etching rate and etching rate of silicon side which is due to the effects of pure chemicals (chemical reaction of fluorine with silicon) decreases rapidly. How gas composition becomes rich in non-reactive components, physical etching processes due to the transfer of kinetic moment of the plasma ions to surface atoms becomes more important, but silicon etching selectivity versus SiO_2 decreases with increasing dilution [4]. Table 5 gives the etching rates of silicon and silicon dioxide in SF_6/Ar pressure of 15 Pa and power density of 0.5 W/cm^2.

Table 5. Si and SiO_2 etching rate and selectivity Si towards SiO_2 in SF_6 + Ar plasma

Plasma SF6/Ar	Si etching rate (nm/min)			SiO_2 etching rate (nm/min)	Selectivity
	Vertical	Horizontal	ratio		
80/20	1000	350	2,9:1	320	3,2:1
50/50	100	37	2,7:1	35	2,8:1
30/70	65	20	3,3:1	28	2,3:1
15/85	35	7	5:1	20	1,7:1

Etching rate of SiO_2 increases with the flow of O_2 until reach a maximum and then decreases at higher O_2 flow rates (Fig. 2). While the low rates of O_2 are released fluorine atoms which leads to an increased concentration of fluorine and hence an increase in the rate of etching at high flow O_2, CO radicals are produced that induce protective polymer. The last effect is similar to the one observed in increasing CHF_3 flow. Also in Fig.1 and Fig. 2 will see a decrease in etching rate with the pressure of the reaction. Oxygen determines the formation of fluorine atoms that increase the etching rate of SiO_2, while atoms of oxygen oxidize photoresist. Etching rate of SiO_2 increases with increasing of ions incidence energy until the etching rate of SiO_2 outstrip that of Si in RIE conditions of high power and low pressure. In dry processes, silicon is engraved with fluorine atoms and SiO_2 is engraved with fluorine ions.

In dry processes, silicon is etched with fluorine atoms and SiO_2 is etched with fluorine ions.

From Fig. 3 we observed that SiO_2 was etched with a very high selectivity to silicon by using a CHF_3 and O_2 gas composition at very low pressure (10 Pa). The etching profile is highly anisotropic using CHF_3 and Ar (Fig. 5).

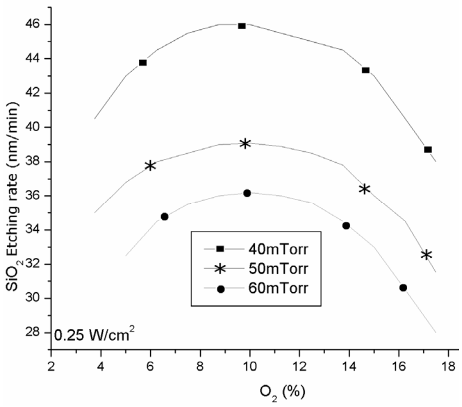

Fig. 2. SiO_2 etching rate dependency of pressure and CHF_3 flow rate. RF power 100W.

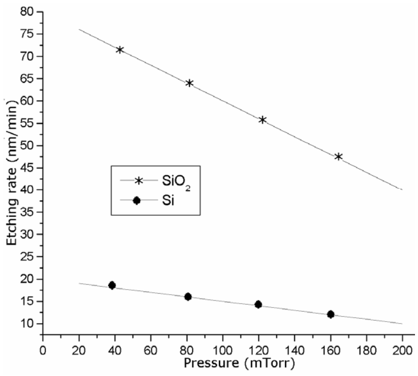

Fig. 3. SiO_2 and Si etching rate dependency of pressure and CHF_3 flow rate. RF power 100W.

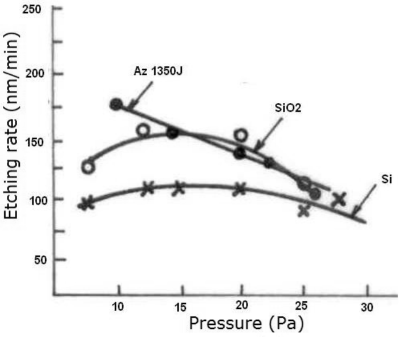

Fig.4. SiO_2, Si and photoresist etching rate dependency of pressure. RF power 100W, CF_4+12%O_2.

By comparing Fig.3 with Fig.4, meaning the etching rate when using CHF_3 and CF_4, respectively, one can easily see, in both cases, the faster etching rate of the silicon oxide related to the etching rate of the silicon. But using CF_4 has a serious drawback, the etching is selective towards silicon but not to photoresist, the photoresist etch rate being similar to the etch rate of the oxide.

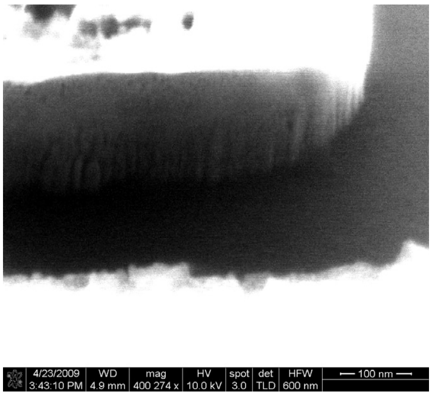

Fig. 5. SEM of anisotropic etching of SiO_2 in CHF_3 and Ar plasma

4. CONCLUSIONS

In this paper were evaluated for the performance of reactive ion etching equipment and were established plasma processing conditions for etching with reactive ions SiO_2, Si, Si_3N_4 and photoresist.

Silicon oxide can be etched with a very high selectivity to silicon by using a CHF_3 and O_2 gas composition at relatively high RF power (250W) and very low pressure (10 Pa). The etch profile in this case is highly anisotropic. In order to achieve selectivity towards the photoresist, the O_2 is replaced by Ar in the gaseous composition.

Silicon etches at high etch rates (about 2µm/min) in SF_6 and O_2 gaseous composition at high RF power (250W) and higher pressure (about 30 Pa), but the etch profile is isotropic. In order to obtain an anisotropic etch profile, O_2 is replaced in the gaseous composition with Ar, thus decreasing the passivation on the side walls but also decreasing the etch rate.

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