Chapter 2

Dry etching characteristics of SiN_x and SiO_x

ICP has been extensively applied to IC manufacturing; owing to its well-controlled etch depth and profile for device fabrication. In order to use this technology for sidewall gate process, an important issue is to achieve a high etching selectivity between SiN_x and SiO_x. By using this technology with optimum process conditions to form the desired sidewall profiles, a reasonable etching rate and selectivity can be achieved. This means that we can over-etch the dielectric layers without changing the gate length too much. SF_6 is applied as the etching gas source to obtain a high etching selectivity of SiN_x/SiO_x.

In addition to achieving a high selectivity, a low surface damage after ICP treatment is needed. Plasma induced damages often results in the degradation of the device performances, such as leakage current and threshold voltage shift, thereby limits the usage of the plasma etching technology in the nano-scale fabrication. Thus, the study of plasma induced damage is also important. The study of reverse breakdown characteristics and surface roughness with and without plasma treatment will be investigated. In this chapter, we describe ICP system, principle of ICP, etching rate, etching selectivity between SiN_x and SiO_x, and the roughness of the etched surface.

2.1 Etching system

The etching experiment was performed by STS ICP system as shown in Fig. 2.1. The ICP etching tool has the advantage of having their impedance matched to that of the plasma and so have a high coupling efficiency between the applied field and electrons in the plasma. In addition, the presence of the solenoidal magnetic filed improves the confinement of the plasma and reduces the losses. Also, as coil and platen power can be varied independently, the etchant species can be increased without increasing the radio frequency power to the substrate. Tools such as the ICP are able to produce high plasma densities at pressures less than 10 mTorr. Low pressure operation helps to reduction scattering and therefore improves the control of etch profiles. BCl_3, SF_6, Cl_2, Ar and O_2 were used as the reactive gases in this system and the gas flow rates were controlled by mass flow controllers. Temperature stabilization of the substrate was achieved by back cooling with helium (He) gas. This was necessary because of the transfer of heat from plasma. The chamber was pumped to low pressure (typically 10^{-7} Torr) by a turbo pump, which was backed by a dry pump [2.1].

2.2 Etching mechanism [2.2]

The etchant could be a liquid, gas, plasma, ion beam *et al.* Inductively coupled plasma uses plasma as the etchant. Plasma is a collection of positive, negative and neutral particles in which the density of the negatively charged particles is equal to the density of the positively charged particles. When an energetic electron hits a neutral reaction gas molecule, it can cause dissociation to form free radicals, ionization, excitation and radiation, as shown in the following equations:

(1) Dissociation: $e^- + AB \rightarrow A + B + e^-$

(2) Ionization: $e^- + A \rightarrow A^+ + 2e^-$

(3) Excitation: $e^- + A \rightarrow A^* + e^-$

(4) Radiation: $A^* \rightarrow A + hv$

Where A^* is the excited states of A.

There are two main types of species, the reactive neutral gas and the ions, involved in the above mechanisms. During the dissociation process, reactive gas molecules are broken into free radicals. Free radicals are neutral atoms which are not affected by the electrical field induced in the reaction chamber and diffuse to the target surface in random directions. Radicals are chemically reactive and are the most important species in the plasma. They are responsible to the surface chemistry.

On the other hand, ions are strongly affected by the electrical field induced in the chamber and are driven to the bottom powered electrode. However, ions are not responsible for chemical reactions. They play a major role in etching rate and anisotropy. Generally, the electron energy required for ionization is much greater than the energy required for dissociation. Very few electrons have the sufficient energy to ionize gas molecules. This is reflected in the relative concentrations of free radicals and ions.

Figure 2.2 illustrates the basic ion etching system. The following processes must take place in the system during ion enhanced etching.

(1) Generation of etching species

(2) Reactive species must diffuse to the sample surface

(3) Gas plasma must adsorb to the sample surface

(4) There must be sufficient energy for the reaction to occur

(5) Volatile products must be formed and desorbed during the reaction

(6) Pump speeds must be sufficient to remove volatile products so new reactive species can be replenished

2.3 Etching selectivity

A high etching selectivity is required for the device fabrication, especially for the fabrication of the sidewall gate process. Selectivity is defined as the ratio of the etching rate of the desired etched material to that of the undesired etched material. Etching selectivity can be maximized by choosing the correct gas or gas mixture that will increase the etching rate of the desired material and decrease the etching rate of the undesired material. In this case, SF_6 based plasmas have been demonstrated as alternative F-atom plasmas in that they leave no carbonaceous residue on surface, which lessens the possibility of roughness, the sidewall gate. The basic mechanism of selectivity etching of SiN_x over SiO_x is formation of SiF_4 (Fig. 2.3) by the following reactions:

$$Si_3N_4 + 4SF_6 \rightarrow 3SiF_4 + 4NF_3 + 4S$$
$$SiO_2 + SF_6 \rightarrow SiF_4 + SO_2 + F_2$$

In particular, one can expect that the etching rate of SiN_x is higher than SiO_x as the strength of a Si-O chemical bond (8.3 eV) is considerably higher than that for a Si-N bond (4.6 eV). Note that the strength of a Si-F bond has an intermediate value of 5.7 eV [2.3].

2.4 Etching experiment

In order to investigate the etching characteristics between SiN_x and SiO_x, gas miture of SF_6+Ar was applied in this study. The flow rate of SF_6 was fixed at 10 sccm, systematically increased the flow rate of Ar. Total gas flow rates and chamber pressure were varied from 10~25 sccm and 5~15 mTorr. ICP source power and RF power were changed from 50 to 150 W and 50 to 90 W, respectively. Samples for the etching study were first deposited SiN_x and SiO_x around 5000 nm on semi-insulating GaAs substrate by PECVD system. Then, samples were patterned with AZ-6112 photo resist baked at 120℃ for 3min. After the ICP etching, the photo resist was removed by ACE and IPA. Then the etching depths of the test samples were measured by the surface profiler (P-10).

2.5 Results and discussion

Figure 2.4 shows the etching rates of SiN_x and SiO_x and selectivity of SiN_x over SiO_x in terms of Ar flow. Addition of Ar into SF_6 ICP plasma dramatically decreases the etching rates of SiN_x, SiO_x and selectivity. The result of 10 sccm of SF_6 ICP plasma without any addition of Ar gives a etching rate of SiN_x and SiO_x, 30.3Å/s and 2.3Å/s, respectively and the etching selectivity of 15. It is noticed that Ar addition increases the physical component of the etching process in the SF_6 plasma. It also implies that reaction becomes more physical than chemical as the Ar flow is increased. These effects increase ion bombardment on the layer and reduce etching selectivity.

Etching rate of SiN_x is a strong function of chamber pressure, but etching rate of SiO_x is not changed significantly as shown in Fig. 2.5. Increasing the chamber pressure, we obtained the higher selectivity value. Higher pressure increases selectivity by reduction of ion energy due to more ion collision. Too low pressure may degrade etching selectivity due to the physical bombardment of highly accelerated ions.

Figure 2.6 shows the etching rates of SiN_x and SiO_x and selectivity as a function of RF chuck power. Once RF chuck power increased from 50 to 90 W, etching rate of SiN_x and SiO_x increases from 18.8 to 25.1 Å/s and 3.85 to 7 Å/s, respectively. Therefore the selectivity decreases dramatically from 4.9 to 3.6. The selectivity is maximized at low RF power.

Figure 2.7 shows the etching rates of SiN_x, SiO_x and etching selectivity *versus* ICP power. The main purpose of ICP power was to increase the density of the plasma. Increasing the power of ICP, the etching rate should be increased. However, the etching selectivity was higher at lower ICP power. In the overall range from 50 to 150 W ICP power, the highest selectivity of 16 could be when the ICP power was 50 W.

Our experimental results demonstrated that the etching selectivity could reach the maximum value when we increased the chamber pressure and decrease RF power. However, the total thickness of the deposited dielectric layer (SiN_x and SiO_x) was around 200 nm. It had better slow down the etching rate as possible, so that the etching depth could be controlled accurately. Therefore, we must get the balance between these two variables (selectivity and etching rates). Finally, we concluded that the gas of SF_6=10sccm, chamber pressure =15 mTorr, ICP power=50W, RF power =50 W, is the optimum condition for sidewall gate process (Fig. 2.8).

In addition to the demands of high selectivity and controllable etching rate, the etch-induced damage has to be minimized to prevent degrading the deice performance. Figure 2.9 demonstrates the surface morphology without plasma treatment. The RMS roughness, evaluated from the atomic force microscopy (AFM) is 1.77 nm. Fig. 2.10 is the AFM image after SF_6 plasma treatment. The average surface roughness is only 3.14 nm, which illustrates this ICP process guarantees a good surface morphology without significant surface damage. The breakdown voltages with and without the plasma treatment are the same (Fig. 2.11). It means that SF_6 plasma for sidewall gate process is a low surface damage process.