OPTIMIZATION OF RF DISCHARGES USED FOR PLASMA ETCHING

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ABSTRACT

Anisotropic plasma etching results from collision free ion bombardment of the wafer. Optimization of the RF discharge in order to obtain an energetic bombardment of this type can be performed with the help of two relationships involving only five parameters, the gas pressure, the plasma density, the electronic temperature, the RF power density and the working frequency.

1 - INTRODUCTION

It has been shown recently by H.F. Winters that electron or ion bombardment of the wafer plays an important role in plasma etching [1]. If the substrate is exposed to halocarbon gases, this bombardment induces dissociation of adsorbed gas molecules and active species are produced in adsorbed phase, an essential step in the etching process. If the wafer is exposed to a plasma such that CF_x radicals are produced in the gas phase, Winters has also demonstrated that adsorption of CF_x radicals is a significant part of the etching process, and that their action is more intense at the position where an electron beam collides with the surface, a fact which can be explained by extra formation of these radicals in the adsorbed phase.

If electron (or ion) bombardment increases the etching speed, it is interesting to use an oriented bombardment of the wafer to induce anisotropic etching, i.e. etching of the bottom of the grooves without destroying the walls, a property highly desirable for producing high packing density Large Scale Integrated Circuits (fig. 1). This is due to the fact that the walls are protected from the charged particle bombardment and are attacked much more slowly by the active etching chemical species : etching rate is consequently much larger from the bottom than from the walls.

An oriented bombardment by plasma particles accelerated perpendicular to the wafer can be obtained if the following conditions are met :

a) The wafer,if conducting,should be sufficiently biased positive or negative by a D.C. voltage.

If the wafer is insulating, D.C. bias cannot be used. The plasma potential should be sufficiently negative with respect to the electrode upon which the wafer is placed.

b) The sheath should be collisionless, i.e. the sheath thickness should be smaller than the electron (or ion) mean free path.

c) The sheath thickness should be much larger than the size of the grooves, to insure a plasma boundary essentially parallel to the wafer.

In these conditions the energy of the ions impinging upon the wafer is the product of their charge by the plasma potential.

The purpose of the present paper is to study the extent to which this oriented bombardment occurs naturally in the type of RF capacitive discharges currently in use for plasma etching, as a function of the main parameters of the discharge:gas pressure, plasma density, power density, working frequency and electronic temperature, if the wafer is placed on one of the electrodes. In this preliminary work, the case of the emitting electrodes is not analysed. For simplicity, a one-dimensional geometry (the so called basic RF plasma diode) is considered here. (fig. 2).

2 - TYPICAL VALUES OF DISCHARGE PARAMETERS IN PLASMA ETCHING

CF_4 or a mixture of CF_4 and O_2, at a pressure between 0.1 and 1 mbar, and at a frequency $\omega/2\pi$ in the 1-30 MHz range are currently used. In a typical case, the RF power density is 36 kW/m^3 [2]. The electron mean free path λ , deduced from the pressure p , from the neutral temperature, and from an approximate value of the elastic collision cross section of 10 Å^2, ranges from 0.3 to 3 mm : it is much larger than the groove thickness ($\simeq$ 1μm). The ion mean free path is four times smaller. The electronic temperature T_e varies from 3 to 8 eV according to the nature of the gas. Its value is predicted from E/p (ratio of the electric field to the working pressure),where E is the AC field (approximation valid if $\nu \gg \omega$, where ν is the electron neutral collision frequency). When ν is predicted from the values of p and T_e , one finds $\nu \simeq 10^9$ s^{-1}, which is much larger than ω.

The electronic density n_e is not known ; this type of discharge has not been subjected to precise measurements, perhaps as a consequence of the difficulty of using Langmuir probes in the presence of RF : if no specific precautions are taken, as for example inserting a high impedance in series near the probe tip and carefully shielding the output, the results can be very misleading, for density determination as well as for plasma potential measurement. One can estimate that this density is typically about 10^{16} m^{-3}. At any rate, it will be shown later that n_e is not relevant for determining the plasma potential, and plays a role only in controlling the sheath thickness.

The Debye radius, deduced from n_e and T_e , is about 100 microns. The thermal sheath thickness is therefore smaller than or at the most equal to the mean free path of the ions. We will show further than the sheath thickness is actually increased beyond that of a thermal plasma, and the problem will arise of keeping this sheath thickness smaller than the ion mean free path. Actually, RF discharges exhibit frequently D.C. plasma potentials of several hundred of volts for an electronic temperature of only a few electron-volts, and larger sheaths than usual are associated with these potentials. This apparent paradox is explained in the present paper, which shows that the plasma potential can be computed from the four following parameters:

- the electronic temperature T_e
- the power density P/V (P : power ; V : volume)
- the working frequency $\omega/2\pi$
- the working gas pressure p .

3 - A GENERAL PROPERTY OF THE PLASMA POTENTIAL IN CAPACITIVE RF DISCHARGES

The following analysis assumes that no electron is emitted from the electrodes. In some cases, particularly when very low frequency is used, the discharge is sustained by an electron current traversing the sheaths from electrode to electrode ; this is not considered here, and we will restrict

our analysis to the conventional case where the discharge is sustained by a current which traverses the sheaths located between plasma and electrodes as a displacement (capacitive) current. This current imposes an RF voltage v_A across the sheath, and, if the frequency is low enough and the power high enough, its RMS value V_A is much greater than the plasma potential due to ambipolar diffusion in a DC discharge at the same electronic temperature.

In the case considered here, an electron crosses the sheath in a time very short compared to the period ($\omega << \omega_p$). This shows that if, at a given time,the voltage v_A across the sheath is such that the plasma potential is negative with respect to the electrode, electrons will be lost almost instantly up to the point where the plasma becomes positive : this mechanism imposes a positive D.C. potential V_p to the plasma, such that V_p is greater than the peak value $V_A \sqrt{2}$ of the AC voltage applied to the sheath. This rectification effect (similar to the behavior of a diode) determines the energy of the ions impinging on the wafer placed upon the electrode. Note that, as the plasma potential adjusts itself to a value such that the electronic and ionic currents leaving the plasma are equal, an insulating wafer has the same surface potential as the supporting electrode if all the electrodes have the same DC potential (no applied bias).

In the case of electron emitting electrodes, the electrons leaving the plasma at one side of the discharge can be partly or totally replaced by electrons emitted from these electrodes and entering the other side : the rectification effect is similar to the behavior of a lossy diode ; the DC potential V_p is then reduced : $V_p = \alpha V_A \sqrt{2}$ with $\alpha < 1$. This case is not considered in our preliminary analysis, and we will also neglect the effect of the electrons thermal velocity on the plasma potential.

This potential is therefore assumed to be given by the formula :

$$V_p = V_A \sqrt{2}.$$

4 - RELATIONSHIP BETWEEN DISCHARGE PARAMETERS AND PLASMA POTENTIAL

The RMS AC voltage across the sheath is :

$$(1) \qquad V_A = i C_o^{-1} \quad \omega^{-1}$$

with $C_o = \varepsilon_o S \ell_o^{-1}$ and $i = (P/R)^{1/2}$

where i is the RMS AC current injected by the RF generator, C_o the sheath capacitance, ε_o the permittivity of free space, S the sheath area, ℓ_o its thickness, P the adsorbed power, R the plasma resistance. Consequently :

$$(2) \qquad \ell_o = \varepsilon_o S \omega V_A (P/R)^{-1/2}$$

The sheath thickness is controlled by Child's law :

$$(3) \qquad \ell_o = 2^{5/4}/3 \quad \varepsilon_o^{1/2} e^{-1/4} \; n_e^{-1/2} \; (kT_e)^{-1/4} \; V_p^{3/4}$$

where k is the Boltzmann constant and e the electron charge. If the relationship $V_p = V_A \sqrt{2}$ is introduced, elimination of ℓ_o between (2) and (3) gives :

$$(4) \qquad e\, V_p . k\, T_e = (2\sqrt{2})^2\, (2/3)^4\, \varepsilon_o^{-2}\, S^{-4}\, (P/R)^2\, n_e^{-2}\, \omega^{-4}$$

The plasma resistance is : $R = e^{-2}\, m\, \ell\, S^{-1}\, \nu\, n_e^{-1}$

where m is the electron mass and ℓ the plasma thickness. Let us introduce the new variables :

(5) $W_+ = e\, V_p$ potential energy of the plasma ions (if ions having unit charge are considered).

and (6) $W_- = P\, \ell^{-1}\, S^{-1}\, \nu^{-1}\, n_e^{-1}$

average energy acquired by an electron between two consecutive elastic collisions.

Using (5) and (6), (4) can be written as follows :

$$(7) \qquad \sqrt{k\, T_e . W_+} = 1{,}26\, (\omega_p/\omega)^2\, W_-$$

The following rule can be formulated :

the geometric mean of the thermal energy of the plasma electrons and the potential energy of the plasma ions is approximately equal to the product of the average energy acquired by the plasma electrons between two consecutive elastic collisions and the square of the ratio of the plasma frequency to the working frequency.

This rule shows, all other parameters being kept constant, that the ions potential energy varies inversely with the fourth power of the working frequency.

The influence of the plasma density, which appears linearly both in the numerator and the denominator of the right hand term of relation (7), vanishes. If the mean free path of the ions λ_i is greater than the sheath thickness ℓ_o, the potential energy of the ions is converted into kinetic energy impinging upon the wafer. In this case, for a given mixture, the anitropy of the etching process is greatest for the lowest frequency consistent with $\ell_o < \lambda_i$. This prediction seems to agree with some experimental observations [3] .

Equation (7) shall be used in conjunction with the inequality $\ell_o < \lambda_i$, with :

$$(8) \qquad \ell_o = m^{-1/2}\, (W_-)^{3/2}\, (kT_e)^{-1}\, \omega_p^2\, \omega^{-3}$$

to determine if the conditions allowing an energetic and anisotropic ion bombardment of the wafer are met for a given set of parameters. These formulas can also be written :

$$(7') \qquad V_p = (1{,}26)^2\, \varepsilon_o^{-2}\, e^3\, m^{-1}\, (P/V)^2\, (kT_e)^{-2}\, \lambda^2\, \omega^{-4}$$

and

$$(8') \qquad \ell_o = \varepsilon_o^{-1}\, e^2\, m^{-3/4}\, (P/V)^{3/2}\, n_e^{-1/2}\, (kT_e)^{-7/4}\, \lambda^{3/2}\, \omega^{-3}$$

If the plasma parameters (plasma density and electronic temperature) were independent of the RF parameters (power density and working frequency), use of equations (7') and (8') for optimization of the etching process would be straightforward.

For example, with $\omega/2\pi$ = 13,56 MHz ; ℓ = 0,04 m ; S = 0,126 m^2 ; P = 200 W ; T_e = 8 eV ; p = 0,1 Torr ; n_e = 4.10^{16} m^{-3} ; ν = $0,5.10^9$ s^{-1} λ = 3.10^{-3} m ; λ_i = $0,7.10^{-3}$ m ; R = 0,1 Ω ; i = 45 A ; W_- = $1,25.10^{-2}$ eV ; $(\omega_p/\omega)^2$ = $1,75.10^4$;V_p = 9500 V and ℓ_o = $1,5.10^{-2}$ m. In this case the sheath is collisional.

If instead of a power of 200 W we use a power of 20 W, with the same values for ℓ , S, T_e , p, n_e and ω, we obtain : V_p = 95 V and ℓ_o =$0.5.10^{-3}$m. In this case the sheath is collisionless.

A problem arises from the fact that n_e and the power density are not independent. Actually,the discharge balance equations couple together these parameters, and limit their choice : it can be shown that to meet the requirement $\ell_o < \lambda_i$, the power density should be kept low and the plasma density high, which is not easily obtained.The result of this study suggests that, to overcome this difficulty, one may produce the plasma with a microwave discharge and use a lower radio frequency for obtaining the required bias at the wafer.

In other applications (deposition of inorganic silicon, for example) anisotropy is not sought and collisions can take place in the sheath. Equation (7') is then useful to assess the extent of ion bombardment of the substrate.

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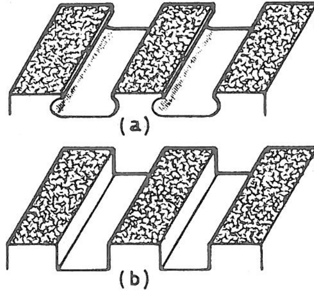

Figure 1 - (a) Isotropic etching.
(b) Anisotropic etching

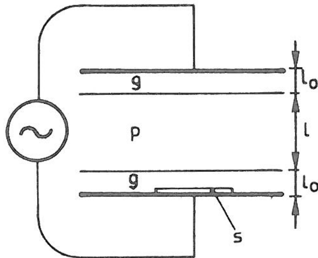

Figure 2 - Discharge geometry

s : wafer
p : plasma
g : sheath