특집論文 89－26－11－5

Design Parameter Analysis for a Planar Type Reactive Ion Etcher

(평판형 반응성 이온 식각기의 설계변수 분석)

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要 約

평판형 구조를 갖는 반응성 이온 식각장치의 몇 가지 중요한 반응로 설계개념을 고찰하였으며, 장치설계상의 한 주요 제한요소로서 식각균일도를 고려하였다. 또한 경제성있는 진공배기계의 특성을 실질적인 설계변수로서 설정하여 분석하였다. 제반 설계의 제한요소를 만족시키는 반응로 구조와 가스공급계 및 진공배기계에 관한 일련의 조건들이 RF 글로우 방전과 가스 유체 역학적인 기본성질로 부터 유도되었다. 그리고, 위의 이론적 결과를 낱장 웨이퍼 처리방식을 갖는 실용적인 평판형 반응성 이온식각기의 설계변수를 추출하는데 적용하였다.

Abstract

Reactor design considerations over several critical parameters for a planar type reactive ion etcher are given. The etch uniformity is taken as a principal design constraint. The characteristics of economically available vacuum pumping system are taken as practical design constraints. A set of theoretical conditions on the chamber geometry and on the gas delivery and vacuum system, that satisfy the design constraints, are derived from basic properties of RF glow discharge and gas dynamics. The theoretical results are applied to decide design parameters of a practical single-wafer-per-chamber planar type reactive ion etching machine.

I. Introduction

For the fabrication of high performance and high reliability microelectronics for electronic and photonic devices, the necessity of etching the substrate anisotropically has been increasing as the pattern size of device decreasing, because an accurate pattern transfer from the resist pattern to the substrate become important and critical process. Plasma assisted dry etching provides an

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接受日字：1989年 7月 1日

(※ 본 연구는 1987년도 한국전기통신공사의 출연금에 의해 수행된 기초과제 연구결과중의 일부임.)

economic and automatic etching technique with high controllability in anisotropy and selectivity while producing little contaminations to the substrate and environment[1,2].

Plasma assisted dry etching equipments may be classified into two categories; the batch type and the single wafer type. The batch type equipments process several wafers at a time, while the single wafer type can process only one wafer at a time. The batch type equipments are well suited for mass production. The single wafer type equipments have better etch uniformity, easier accessibility for maintenance, and better process flexibility. For a process that requires exact process control for each wafer, the single wafer type equipments are preferred.[3] The most popular reactor geometry for the single wafer type equipments is the planar geometry operated in Reactive Ion Etching (RIE) mode which can give highly anisotropic etching in higher process pressure ranges (1-1000 m Torr).

In this work, we concentrate on design parameter analysis for a planar type reactive ion etcher. The etch uniformity is taken as a principal design constraints. The characteristics of economically available vacuum pumping system are taken as practical design constraints. A set of conditions on the chamber geometry that satisfy the design constraints are derived from basic properties of RF glow discharges and gas dynamics. Design considerations for the process chamber are given in section II. The vacuum and gas delivery system are considered in section III. Results are summarized and discussed in section IV.

II. Chamber Design Consideration

1. Theory

In order to facilitate the chamber design process, we consider simple physics governing the RF discharge process. We assume a planar electrode geometry given in Fig.1, and also assume that the RF zero-to-peak voltage across the electrodes is V volts (200-300V typical). Then, without plasma, the RF electric field between the electrodes is given by

$$\varepsilon = \frac{V'_{rf}}{d} = \frac{V}{d}\sin\omega t \qquad (1)$$

Using Eq.(1) and the equation of motion for the species s

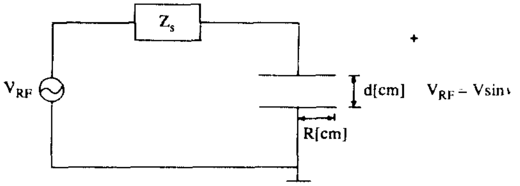

Fig.1. A planar parallel electrode model for RF discharge.

$$m_s\dot{x} = q_s\varepsilon,$$

we have the rms velocity and distance for the electron motion under the RF electric field;

$$\langle\dot{x}\rangle = \frac{1}{2}\frac{eV}{m_e\omega d}, \qquad (2)$$

$$\langle x\rangle = \frac{1}{2}\frac{eV}{m_e\omega^2 d}. \qquad (3)$$

These formula apply for the motion of electrons in a low pressure discharge, i.e., the electron mean free path λ_e is much greater than the rms electron motion $< x >$. For this case, the average electron energy E_e becomes $m_e\omega^2 < x >^2 /2$. The mean free path is defined by

$$\lambda_e \equiv \frac{1}{n_n\sigma} \qquad (4)$$

where n_n is the neutral density and σ is the electron-neutral collision cross-section (10^{-14} - 10^{-15} cm^2 typically). We assume that the background gases are at room temperature. Then, the electron mean free path λ_e in Eq.(4) can be rewritten as

$$\lambda_e = \frac{kT}{P_n\sigma} \simeq \frac{6.2}{P_n[\text{mTorr}]}\ [\text{cm}] \qquad (5)$$

where, $k = 1.3807 \times 10^{-16}$ erg/deg(K) is the Boltzmann constant, and P_n is background neutral pressure. We assumed that $\sigma \sim 5 \times 10^{-15}$ [cm^2] for a typical process that we consider. For the case of $< x > >> \lambda_e$, the electrons gain energy from the electric field over the distance λ_e, and the electron energy becomes

$$E_e \sim e\varepsilon\lambda_e = \frac{eV}{d}\lambda_e \qquad (6)$$

Since it it required that $E_e >> F_{\text{ionization}}$ for the ignition of RF discharge, we can obtain the required gap spacing d for a given range of pressure and RF voltage. Consequently, for higher pressures, less gap spacing is required. For a fixed gap spacing, higher pressures require higher electric field strengths, i.e., higher power densities.

Once the condition that the electrons acquire enough energy from the RF electric field to ionize background neutral gases and ignite RF discharge, it is necessary to confine the electrons to sustain the RF discharge. The necessary condition is that the classical electron confinement time τ_c is much longer than the electron-neutral collision time. This condition implies that any electrons, created whatever means, stay in the system long enough to be heated by the RF electric field and to generate at least another electron-ion pair so that the discharge process continues. The plasma density increases until the plasma loss coming from the electron-ion recombination, the diffusion to the wall, etc., balances the plasma creation.

In the steady state, the difference in the mobilities between ions and electrons induces the ambipolar field so that the electron and ion loss rate be the same, i.e., the diffusion process becomes ambipolar. The ambipolar diffusion constant D_a is defined by[4]

$$D_a \equiv \frac{\mu_i D_e + \mu_e D_i}{u_i + \mu_e} = \left(\frac{T_e}{T_i} + 1 \right) D_i$$

where $\mu_s \equiv e_s/m_s v_s$ is the mobility for the species s, and $D_i \equiv T_i/m_i v_i$ is the classical diffusion constant for ions. Typically $T_e/T_i \sim 100$ (T_i:0.04 ~ 0.1eV), and we have

$$D_a \approx \frac{T_e}{T_i} \cdot D_i \tag{7}$$

Assuming that the classical ion diffusion velocity is the same as the ion thermal velocity, the ambipolar diffusion velocity u_a is approximately given as

$$u_a \approx \frac{T_e}{T_i} \quad v_i \tag{8}$$

Then, from the diffusion equation

$$n_i u_a = - D_a \nabla n_i$$

we have a characteristic distance L_a for the variation of the plasma density as

$$L_a \approx \frac{D_a}{u_a} \tag{9}$$

Next, we concentrate to the problem of choosing a proper electrode to wall distance. We assume the chamber geometry given in Fig. 2. Here, the upper electrode is electrically connected to the perfectly conducting chamber wall and the RF power is applied to the bottom electrode. In order to reduce the direct RF leakages from the bottom electrode to the wall, we need to have the conductivity between the wall and the bottom electrode much smaller than the conductivity between the electrodes, i.e., $C_{chamber} << C_{electrode}$. We approximate $C_{chamber}$ with a concentric capacitor model, and $C_{electrode}$ with a parallel capacitor model;

$$C_{chamber} \approx 2\pi\varepsilon_0 \ell \ln\frac{R+2r}{R}$$

$$C_{electrode} \approx \frac{\varepsilon_0 A}{d}$$

Then, the condition $C_{chamber} << C_{chamber}$, requires

$$1 + \frac{2r}{R} << \exp\left(\frac{R^2}{2d\ell} \right) \tag{10}$$

This condition can easily be satisfied with $r < R$ and $R^2 > d\ell$, implying that the direct RF leakage from the bottom electrode to the wall is not an important design consideration.

Another aspect related to the RF field that deserves our attention is the fringe effects. To give an uniform electric field inside the electrodes, we should suppress the fringe effects as much as

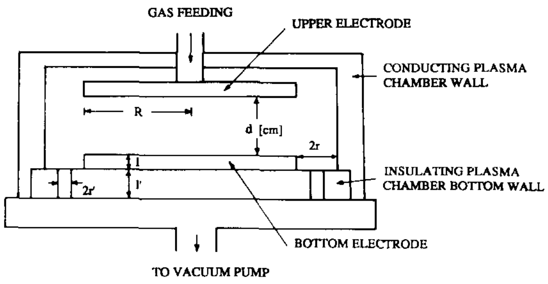

Fig.2. A schematic diagram of the plasma chamber geometry.

possible. For a lower density plasma (during ignition), the condition $r << R$ is practically very difficult to be satisfied. However, once we have plasma, the plasma provides a good conductivity inside it, so that the dominant distance governing the fringe effect is the sheath thickness which is a couple of time longer than the Debye length λ_D[4,5];

$$\lambda_D^2 \approx \frac{kT_e \varepsilon_0}{n_e e^2} \qquad (11)$$

So, if we choose the electrode to wall distance 2r to be much larger than the sheath thickness, the perturbation on the electric field from the wall is negligible. This result implies that the electrode to wall distance 2r is mainly determined from the requirements of the plasma residence time for a given pumping speed. We will consider this problem in the next section.

Finally, we consider the shower head on the upper electrode assembly. We assume that the geometry of the shower head which satisfies the vacuum requirements is already given, i.e., ω cm for the hole size and Δ cm for the hole spacing. Then, the characteristic diffusion time for the neutrals to have an uniform density profile is

$$\tau_n = \frac{\Delta^2}{D_n} \approx 3 \ [\mu\text{sec}]$$

showing that the pressure nonuniformities stemming from the spacing of the shower hole is negligible for an usual semiconductor processing. Here, we assumed that the neutral atom is hydrogen with the temperature T_n = 300 K, and the pressure P_n = 200 mTorr, and assuming that the hole spacing Δ = 1 cm. For heavier neutrals, the diffusion coefficient decreases by factor $Z^{-1/2}$, increasing τ_n by factor of $Z^{1/2}$ that is still negligible compared to the gas residence time. Here, the Z is the atomic mass number. The detailed calculation for determining the hole size and the hole spacing will be given in the next section.

2. Design Consideration

In this subsection, starting with reasonable assumptions on the dry etching process parameters, we choose a set of chamber design parameters that satisfy the required conditions given in the previous subsection. First, we consider a process chamber that can handle 8 inch wafers. We choose that the electrode radius R = 10.8 cm (~ 8 1/2" diameter) and the electrode separation d = 3/16" ~ 2" (0.5-5 cm), and assume that the RF driving frequency is 13.56MHz, $T_{gas} \sim$ 300 K, $T_e \sim$ 1eV, P=50-1000 mTorr (200 mTorr typical), and V = 200-300V (typical). Then, from Eq. (5), the electron mean free path λ_e for P= 200 mTorr is

$$\lambda_e = 3.1 \times 10^{-2}\,\text{cm}$$

and, from Eq.(2), the collisionless rms electron motion $<x>$ becomes

$$\langle x \rangle = \frac{1}{2} \frac{1.6 \times 10^{-19} \cdot 200}{9.1 \times 10^{-31} \cdot (8.5 \times 10^7)^2} \frac{1}{d[m]} \ [m]$$

$$\sim \frac{25}{d[cm]} \ [cm] \ >> \lambda_e \qquad (12)$$

showing that the process is collision dominated. Because of the condition in Eq.(12), we use Eq.(6) for the electron energy calculation, i.e.,

$$E_e \sim \frac{200}{d} \lambda_e \ [eV]$$

resulting $E_e \sim$1.24 eV for d=5 cm and $E_e \sim$12.5 eV for d= 0.5 cm. Considering the ionization energies; 15.56eV for nitrogen, 12.2-12.5eV for oxygen, 11.47eV for chlorine, 15.6-15.83eV for fluorine, etc., the above calculation shows that we might have some difficulties to ignite RF discharge. To remedy this problem, we need to either decrease the gap spacing and/or decrease the background pressure, or increase the RF voltage (power). The validity of the above calculations are based on the high background pressure (electrodes are not important for this case),i.e.,

$$\frac{\lambda_e}{d} \sim O \ (10^{-1}) \ << 1$$

and the high collisionality, i.e.,

$$\frac{\nu_e}{\omega} = \frac{v_e}{\lambda_c \omega} \sim O \ (10^2) >> 1$$

where ν_e is the electron-neutral collision frequency. We will assume that the electrons can gain enough energy to ignite the RF discharge bv increasing the RF voltage. The electron temperature T_e is somewhat lower than E_e because the electrons are cooled off by collisions with ions and neutrals (mainly by neutrals), and we choose T_e=1eV for the following calculations.

The average electron velocity υ_e is

$$\upsilon_e = \left(\frac{2eT_e}{m_e}\right)^{1/2} = 5.8\times 10^7\ [\mathrm{cm/sec}]$$

and the electron neutral collisional frequency becomes

$$\nu_e = 1.87\times 10^9[\mathrm{sec}^{-1}] >> f = 13.56\mathrm{MH_z}$$

so that we only need to consider the classical diffusion process to examine whether the discharge process continues or not. The electron diffusion constant is defined by $D_e=T_e[eV]/m_e\nu_e$, and we have

$$D_e = \frac{\upsilon_e^2}{\nu_e} = \upsilon_e \cdot \lambda_e = 1.8\times 10^6\,[\mathrm{cm^2/sec}]$$

Then, from the diffusion equation for electrons

$$n_e\vec{u}_e = -D_e \nabla n_e$$

and

$$\frac{\partial n_e}{\partial t} + \nabla \cdot (n_e\vec{u}_e) = 0$$

we obtain the electron confinement time for the case of d << R as

$$\tau_c \approx \frac{d^2}{4D_e} = 3.8\ [\mu\mathrm{sec}]$$

that is 10^5 times larger than the electron-neutral collision time, implying that the discharge continues.

Next, we consider the necessary conditions on the electrodes for uniformly etching 8" wafers. With T_i=0.05eV and T_e/T_i=20, the ambipolar diffusion constant D_a, which is given in Eq.(7), is

$$D_a = 1.38\times 10^5\ [\mathrm{cm^2/sec}]$$

and the ambipolar diffusion velocity, which is given in Eq.(8), becomes

$$U_a = 4.4\times 10^6\,[\mathrm{cm/sec}]$$

Then, the characteristic distance L_a, given in Eq.(9), for the variation of the plasma density is

$$L_a = 3.1\times 10^{-2}\ \mathrm{cm}$$

for P_n=200 mTorr. In the case of P_n=20 mTorr, D_a increases by a factor of 10 so that

$$L_a = 3.1\times 10^{-1}[\mathrm{cm}] < 1/4''$$

ensuring relatively uniform plasma density within the radius of R-L_a cm. This result shows that taking the electrode radius 1/4" larger than the largest possible wafer radius is a reasonable choice for the process pressure range of 10 to 10^3 mTorr!

Finally, we consider the fringe effects. Here, we assume that the degree of ionization is 10^{-6} of available neutrals (10^{-4} - 10^{-6} in most of the plasma etching machines). Then, the electron density n_e is

$$n_e = \frac{0.2}{760}\cdot\frac{6.02\times 10^{23}}{22.4\times 10^{-3}}\cdot 10^{-6} = 7.07\times 10^{15}\quad [\mathrm{electrons/m^3}]$$

resulting

$$\lambda_D = 8.81\times 10^{-3}\,[\mathrm{cm}]$$

and we expect that the sheath thickness is smaller than 0.1 cm. Because the sheath thickness is much smaller than both L_a and 2r, we expect the fringe effects to be negligible.

III. Vacuum and Gas Feeding System Design Considerations

The parameters that impose practical design limitations on the gas feeding and vacuum system are the process chamber pressure P, the liquifying pressure P_L of the inlet gas, the maximum allowable inlet pressure of the Mass Flow Controller (MFC) P_{MAX}, the maximum inlet-outlet pressure difference P_{MAX} of the MFC, and the minimum inlet pressure P_{pump} of the vacuum pump for efficient pumping. For any dry etching processes using gases with lower P_L (e.g., BCl_3, CCl_4, etc.), a great care should be done to prevent the differential pressure P_{dif} of MFC being greater than the liquifying pressure P_L. Here, we assume that the parameters P, P_L, P^{MAX}, and P_{pump} are known from the process requirements and the limitations on the economically available MFCs and pumps, and investigate the design constraints on the shower-head and the exhaust manifold.

We use the following basic vacuum equations;

$$Q_M = \frac{dG}{dt} \tag{13}$$

$$Q_{pv} = \frac{d(PV)}{dt} \tag{14}$$

$$S = \frac{dV}{dt} \tag{15}$$

$$PV = \frac{G}{M} RT \tag{16}$$

where, M is the molar mass of gas, G is the mass of gas contained within a volume V , and R is the molar gas constant, Q_M is the mass flow rate, Q_{pv} is the gas flow rate in the pressure unit, and S is the pumping speed. For a constant temperature process, the flow rate (14) may be expressed by

$$Q_{pv} = \frac{PV}{G} Q_M$$

and, for a steady state system, the effective pumping speed S_{eff} may also be expressed in terms of the flow rate Q_{pv};

$$S_{eff} = \frac{Q_{pv}}{P}$$

where

$$\frac{1}{S_{eff}} = \frac{1}{S} + \frac{1}{C_{exh}}$$

and C_{exh} is the flow conductance of the exhaust manifold.

In order to improve process uniformity, we need to have a uniform gas feeding into the process chamber through a shower head. A sketch of a typical shower head geometry is given in Fig. 3. Here, h is the height of the gas reservoir, R is the radius of the shower head, w is the diameter of the shower hole, h' is the effective length of the shower hole, and r_0 is the diameter of the gas line. We assume that the ratio w/h' is small and the shower holes are uniformly spaced throughout the bottom side of the shower head. A prerequisite for an uniform gas feeding to the process chamber is an uniform pressure distribution, within the gas reservoir.

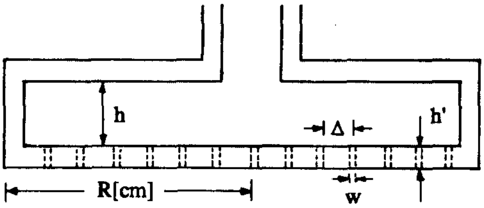

Fig.3. A sketch of a typical shower head geometry.

We assume that the radial flow conductance per unit volume of the gas reservoir is C_1 [ltr·(sec·cm^3·Torr)$^{-1}$], and the flow conductance of the shower holes per unit area is C_2 [ltr·(sec·cm^2·Torr)$^{-1}$]. We also assume that the total flow rate at the radius r is Q_{pv} [ltr/sec]. Then, the pressure and the flow profiles are determined by the differential equations;

$$\frac{dP}{dr} = -\frac{Q_{pv}}{2\pi r h C_1} \tag{17}$$

$$\frac{dQ_{pv}}{dr} = -2\pi r P C_2 \tag{18}$$

Differentiating Eq.(17) with respect to r and using Eq.(18), we have

$$\frac{d^2P}{dr^2} + \frac{1}{r}\frac{dP}{dr} = \beta P \tag{19}$$

where

$$\beta \equiv \sqrt{C_2/(hC_1)}\,.$$

Eq.(19) is the modified Bessel's equation governing the radial pressure profile in the gas reservoir. General solution of Eq.(19) is given as

$$P = \alpha_1 I_0(\beta r) + \alpha_2 K_0(\beta r). \tag{20}$$

Applying the boundary conditions, that $P=P_0$ for $r < r_0$ and $\partial P/\partial r = 0$ at the side wall, to Eq.(20), we have

$$P(r) = P_0 \frac{K_1(\beta R) I_0(\beta r) - I_1(\beta R) K_0(\beta r)}{K_1(\beta R) I_0(\beta r_0) - I_1(\beta R) K_0(\beta r_0)}, \; r > r_0 \tag{21}$$

In the limiting case of $\beta r_0 \gg 1$, $K_0(\beta r_0)/I_0(\beta r_0) \to 0$, $I_0 \approx I_1$, and $K_0 \approx K_1$. Then, the pressure

$P(r) = 0$ for $r < r_0$ and $P(r) = P_0$ for $r < r_0$, corresponding to the case that the shower hole's flow conductance is too large to fill up the gas reservoir. In the other limiting case of $\beta R << 1$, $I_0(x) \rightarrow 1$, $I_1(x) \rightarrow x/4$, $K_0(x) \rightarrow -\ln(x/2) + 0.5772 \ldots$, $K_1(x) \rightarrow 1/x$, $I_0(\beta r_0) << K_0(\beta r_0)$, and $K_0(\beta R) < K_1(\beta R)$. Approximating Eq.(21) under this condition, we have

$$P(r) = P_0 \frac{K_1(\beta R) - I_1(\beta R) K_0(\beta r)}{K_1(\beta R) - I_1(\beta R) K_0(\beta r_0)} \approx P_0$$

So, the condition for a constant pressure profile in the gas reservoir is

$$\beta << \frac{1}{R}$$

Since,

$$C_2 \approx \frac{C_{hole} \cdot n_{tot}}{\pi R^2}$$

where C_{hole} is the flow conductance of each of the shower hole and n_{tot} is the total number of the shower holes, we can rewrite the above condition as

$$n_{tot} \cdot C_{hole} << \pi h C_1 \qquad (22)$$

This condition for an uniform pressure profile in the shower head gas reservoir can easily be satisfied. For example, if we choose h=1cm, ω=0.1cm, and h'=1cm, $\mu h C_1$/hole is approximately. 2.7 x 10^3. So, if we take n_{not} =200, the condition (22) is satisfied. Here, we used the following formula in the reference (6) for the flow conductances;

$$C^{laminar}_{circular} \approx 135 \, \frac{d^4}{\ell} \, \frac{P_1 + P_2}{2}$$

for a circular pipe with ℓ [cm] in length, d [cm] in diameter, P_1 [mbar] for the inlet pressure, and P_2 [mbar] for the outlet pressure. For the calculation of the flow conductance C_1, we approximated the gas reservoir with a set of rectangular pipes and used the above formula with correction factor 0.88.

Once the condition for uniform pressure profile is satisfied, the next question is whether the above condition satiefies the process requirements. For a typical dry etching process, the range of process pressure is 10 mTorr to 1 Torr, and the range of the mass flow rate Q_M is 10 SCCM to 500 SCCM. The unit SCCM stands for Standard CC per Minute. The conversion factor of SCCM to the pressure unit is 1 SCCM=1/79.05 Torr ltr/sec, and the upper limit of the flow rate in the pressure unit becomes

$$Q^{MAX}_{pv} = 6.32 \, \mathrm{Torr \cdot ltr/sec.}$$

Then, the required flow conductance for the shower head is

$$n_{tot} C_{hole} (P_{res} - P) = N Q^{MAX}_{pv}$$

where P_{res} is the pressure of the gas reservoir and N is the number of the gas channels. (In order to prevent liquifying the process gases, it is necessary to choose $P_{res} < P_L$ - 70 Torr).

Finally, we consider the conductance requirements of the exhaust holes. For this purpose, we assume that the flow conductances of the throttling value and the exhaust lines are much larger than that of the exhaust holes. The lower limit of the flow conductance of the exhaust holes is determined mainly from the pumping efficiency at lower pressure ranges. For a typical root pump, the pumping speed drops rapidly with the inlet pressure P_{exh} less than 5 mTorr[6]. Since the lower limit of the process pressure is given to be 10 mTorr, the flow conductance of the exhaust holes needs to be

$$C_{exh} = \frac{\Sigma Q_{pv}}{5 \, [\mathrm{mTorr}]}$$

We use the Prandtl's formula[6] for the flow conductance of an aperture of surface area A cm^2;

$$C_{exh} \sim 40 A \ \mathrm{ltr/sec}$$

Assuming that N=4 and $\Sigma Q_{pv} = N Q^{MAX}_{pv} = 6.32N$ Torr ltr/sec, we have the maximum required exhaust hole opening as

$$A_{MAX} \sim 126 \, [\mathrm{cm}^2]$$

However, for typical low pressure processings, $\Sigma Q_{pv} < Q^{MAX}_{pv}$ and we have

$$A < 31.5 \, [\mathrm{cm}^2]$$

which is less strict.

IV. Summary

In designing a reactive ion etcher, the principal design constraint is the etch uniformity, and the practical design constraints are the characteristics of economically available vacuum pumping system.

The most critical design parameter for improving the etch uniformity is the characteristic length for plasma density variation, that is given by $L_a \approx D_a/U_a$. In order to ensure the etch uniformity, the distance from the edge of wafer to the edge of the bottom electrode should be larger than L_a.

For uniform gas feeding, we adopted a shower head, and the shower head should satisfy the condition $n_{tot} C_{hole} << \pi h C_1$. For efficient pumping, the vacuum exhaust manifold should satisfy $C_{exh} > \Sigma Q_{pv}$ /5mTorr, i.e., $N \cdot Q^{MAX} < 40A \cdot P_{MAX}$ for our geometry.

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