Simulation of Dual-Electrode Capacitively Coupled Plasma Discharges

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Abstract Dual-electrode capacitively coupled plasma discharges are investigated here to lower the non-uniformity of plasma density. The dual-electrode structure proposed by Jung splits the electrode region and increases the flexibility of fine tuning non-uniformity. Different RF voltages, frequencies, phase-shifts and electrode areas are simulated and the influences are discussed. RF voltage and electrode area have a non-monotonic effect on non-uniformity, while frequency has a monotonic effect. Phase-shift has a cyclical influence on non-uniformity. A special combination of 224 V voltage and 11% area ratio with 10 MHz lowers the non-uniformity of the original set (200 V voltage and 0% area ratio with 10 MHz) by 46.5%. The position of the plasma density peak at the probe line has been tracked and properly tuning the phase-shift can obtain the same trace as tuning frequency or voltage.

Keywords: dual-electrode, non-uniformity, capacitively coupled plasma, fluid model

PACS: 52.50.Qt

DOI: 10.1088/1009-0630/18/12/06

1 Introduction

Capacitively coupled plasma (CCP) discharges are widely used in microelectronic fabrication such as etching and thin-film deposition [1,2]. Capacitively coupled plasma is generated by parallel electrodes with RF sources under low pressure. Both single-frequency and dual-frequency CCP discharges are used in etching or deposition [3–8]. Dual-frequency control of CCP is widely adopted with its effective control of the separation between plasma density and ion bombardment energy [9–13].

Improving the non-uniformity of plasma density is a traditional problem in the semiconductor process. With the development of semiconductor processing technology, the process system with large wafer area driven by high frequency has attracted a great deal of attention. The plasma density and etching/deposition rates become denser with the increment of RF frequency, and the ion bombardment energy decreases with the lower frequency source voltage reduced. But the non-uniformity of plasma density deteriorates with the higher frequency and larger wafer area [14–20]. With the wafer scale transition from 300 mm to 450 mm in the semiconductor industry, the non-uniformity of plasma causes more defects, such as chips on the wafer have different quality, and over-treated or under-treated chips ascend. Defects due to non-uniformity should be improved. In fact, the non-uniformity of plasma is affected significantly by electromagnetic effects with ultrahigh frequency [21]. An optical probe is adopted to measure the uniformity of plasma [22].

There are many methods studied to lower the non-uniformity of plasma density. Schmidt found that non-uniformity can be lowered by special shaped electrodes driven by high RF frequency, such as lens electrodes [23,24]. The special shapes increase the difficulty of electrodes design and production. Phase shift is another way to obtain the same result in which the same frequency RF sources are applied on paralleled electrodes with phase shifts [25,26]. The phase shift control in reducing the non-uniformity has been proved in experiments and simulations. Chen simulated the segmented powered electrodes structure with self-consistent plasma models [27]. Jung suggested a multi-electrodes design to lower the non-uniformity and configured a dual-electrodes system with equal electrode area to test [28]. The non-uniformity of Jung’s system lowered 3%, but the details and mechanism of parameters affecting the non-uniformity were not discussed. Dual electrodes CCP discharge simulations are implemented with the plasma fluid model and influences of RF voltage, frequency, phase-shift and electrode area on non-uniformity of plasma density are discussed in this study.

This paper is organized as follows: section 1 introduces the background, sections 2 and 3 show the chamber geometry and the plasma fluid model adopted. Section 4 simulates and discusses the electrodes area ratio, RF voltages, frequency, phase-shift’s influence on the non-uniformity of plasma density.
2 Geometry model

The discharge chamber is an axisymmetric 2D structure as shown in Fig. 1. The uniformity of plasma density is affected remarkably by the wafer scale larger than 450 mm. The diameter of the chamber is 500 mm. Electrodes 1, 2 and the dielectric ring are in a concentric structure. The radius of electrode 1 is 200 mm, the width of electrode 2 and the dielectric ring are both 25 mm. The radius of two concentric electrodes is 225 mm. The inner height of the chamber is 30 mm. The thickness of the two electrodes and the dielectric ring are 2 mm. The electrodes are dielectric plates with relative permittivity 4.2 as the dielectric ring. The probe line is placed 10 mm above the upper side of electrodes and its length is 225 mm as long as two electrodes. The RF sources are applied to the exterior boundary of the dielectric plates shown in Fig. 1. The top and side walls are grounded. Electrodes 1 and 2 are connected to the RF sources with different electric parameters in the simulations.

Fig. 1 The sketch of the dual electrodes chamber structure

3 Governing equations and reactions

The traditional fluid model is adopted here in plasma simulations. For electrons, the density and electron temperature are computed by solving electron drift and diffusion equation and electron energy equation. For ions, the density is computed by solving the ion drift and diffusion equation. The ion energy equation is not solved and the background gas energy is taken as the ion energy. The electric field and potential are computed by solving the Poisson equation.

Only ionization reaction of argon is chosen in simulations: e+Ar=2e+Ar-. Metastable atoms are ignored. Elastic, excitation collisions are not considered. Cross section data are taken from the Phelps database. The magnetic fields are not considered for the frequency 10 MHz in this study. The discharge pressure is 100 mTorr under which the electron energy distribution function follows a Maxwellian distribution. Commercial code COMSOL 4.4 is adopted to implement the simulations. The fluid model used here is based on the electrostatic model and it cannot capture the electromagnetic effect without the magnetic field being solved. The ion inertia effect is not included for the ion drift-diffusion approximation.

4 Results and discussions

Lowering the non-uniformity of plasma density is a significant demand in etching or deposition in semiconductor manufacture. The bulk plasma has a good uniformity. The edge of plasma descends sharply lowering the uniformity of plasma density. The plasma density is affected by the structure of electrode, RF voltage, frequency and phase-shift. Adjusting the above parameters could be helpful in improving the non-uniformity. In the following simulations, the parameters of electrode 1 are kept constant but the parameters of electrode 2 are adjustable.

4.1 Distribution of plasma density

The comparison of four different sets of cases is shown in Fig. 2. Cases 200 V-10 MHz-0, 220 V-10 MHz-0, 200 V-10.005 MHz-0 and 200 V-10 MHz-1.8π are simulated to distinguish the dual electrodes from a single electrode about the effect on the nonuniformity of electron density. The label 200 V-10 MHz-0 represents the voltage 200 V of electrode 2 with driven frequency 10 MHz and 0 phase-shift for example. Electrode 1 keeps 200 V voltage, 10 MHz frequency and 0 phase-shift in four cases. The electron density distribution of a traditional single electrode is shown in the 200 V-10 MHz-0 case. Another distribution line shows the electron density of 220 V-10 MHz-0 which only increases the RF voltage by 10% on electrode 2. The third distribution line shows the case with 200 V voltage on electrode 2 but different driven frequency 10.005 MHz. The fourth distribution line shows the case with a different phase-shift of 1.8π. The plasma density divided by 1016 m^-3 is a dimensionless quantity. The radius is normalized by half of the external diameter of electrode 2. The vertical line indicates the position of the interface between electrodes 1 and 2. The radius of electrode 1 is 200 mm, which is equal to 0.89 in the x coordinate.

Fig. 2 Comparison of electron density with different RF voltages, frequencies and phase-shifts: 200 V-10 MHz-0, 220 V-10 MHz-0, 200 V-10.005 MHz-0 and 200 V-10 MHz-1.8π on electrode 2 and 200 V-10 MHz-0 on electrode 1.

The density descends sharply on the edge of the electrode for an edge effect both in single and dual
electrodes. The density jumps intensely on the right hand side of the vertical line due to the increment of voltage on electrode 2 in case 220 V-10 MHz-0. The increment of the voltage leads to the increased power absorption in plasma and the electron density ($n_e$) slightly denser in bulk plasma with 220 V-10 MHz-0 than 200 V-10 MHz-0. The peak near the edge reverses the descend trend of the density and forms the shape of a paddle. Compared to 200 V-10 MHz-0, the driven frequency 10.005 MHz which applied to electrode 2 with 0.05% increment of 10 MHz brings a higher peak density at bulk plasma and a more sharply descending curve tail. The plasma density peak is proportional to frequency square and RF voltage just as the relationship in a single frequency discharge,

\[ n \propto \omega^2 V_{\text{rf}}. \]

The phase-shift $1.8\pi$ brings a distribution line similar to the voltage 220 V case but a much higher peak on the right side of the vertical line. The distribution of plasma density depends on the configuration of the discharge structure.

The standard deviations of electron density on the probe line in cases 200 V-10 MHz-0, 220 V-10 MHz-0, 200 V-10.005 MHz-0 and 200 V-10 MHz-1.8$\pi$ are 0.54769, 0.30962, 0.65973, and 0.41201, respectively. The nonuniformity changes $-43\%$ from 200 V to 220 V, $+27\%$ from 10 MHz to 10.005 MHz and $-25\%$ from 0 to $1.8\pi$. The standard deviation is taken as an indicator of non-uniformity here.

### 4.2 Influence of parameters

The electron density distributions affected by area ratio, voltage, frequency and phase shift are shown in Fig. 3. Different parameters of electrode 2 are simulated to investigate the influence on the non-uniformity of electron density. Total radius of electrodes 1 and 2 is 225 mm, which is denoted as $r_0$ in the figures below. The horizontal ordinate is normalized by $r_0$ (225 mm), and the vertical ordinate is divided by $1\times10^{16}$ (m$^{-3}$) to eliminate the high order of magnitude.

#### 4.2.1 Distribution of $n_e$

The area of electrode 2 affects the non-uniformity of plasma generated. The distributions of electron density of the probe line with the area ratio from 0% to 75% are presented in Fig. 3(a). The voltage of electrode 2 is 220 V and the voltage of electrode 1 is 200 V. RF driven frequency is 10 MHz. The original case 0% is set as a reference. The plasma density curve’s tail is lifted higher with the increase of the area ratio. The region affected by the RF voltage increases with the area of electrode 2. The increase of ratio equals to the increase of power input. For 9.5 Ne near the average electron density, the non-uniformity of ratio 19% and 21% is better than others.

Voltage of the electrode 2 is another factor that affects the non-uniformity of plasma. The distributions of electron density of the probe line with the voltage increment from 0% to 18% are shown in Fig. 3(b). The RF voltages of electrodes 2 and 1 are denoted as $V_2$ and $V_1$ in the figures below. Different voltages of electrode 2 are simulated and $V_1$ is kept 200 V. RF driven frequency is 10 MHz. The area ratio of electrode 2 to the total area is kept at 21%. The plasma density curve above electrode 2 gradually rises with the voltage increase. The increase of voltage equals to the increase of local power deposition.

![Fig.3](plasma_density_distribution.png)
The frequency of electrode 2 is the third factor that affects the non-uniformity. The distributions of electron density of the probe line with the frequency increment from 0% to 0.5% are shown in Fig. 3(c). RF frequencies of electrodes 2 and 1 are denoted as \( f_2 \) and \( f_1 \) in the figures below. Different frequencies of electrode 2 are simulated and driven frequency \( f_1 \) is kept 10 MHz. Both RF voltages of electrode 1 and 2 are kept at 200 V. The area ratio is 21%. The plasma density curve above electrode 1 rises with the frequency increase. The region affected by the RF frequency expands with the increase of the frequency of electrode 2. The main part of the curve rises and the peak increases in the region above electrode 1 and the tail curve falls below the reference in the region above electrode 2 with the increment of electrode 2 frequency. The peak rises sharply which means that plasma density is sensitively affected by frequency.

The phase-shift of electrode 2 is the fourth factor that affects the non-uniformity of plasma. The distributions of electron density of the probe line with phase-shifts from 0 to \( 2\pi \) are shown in Fig. 3 (d1) and (d2). Phase-shifts are divided by \( 2\pi \) to be normalized. Different phases of electrode 2 are simulated and the phase of electrode 1 is kept at 0. Both RF voltages of electrodes 1 and 2 are kept at 200 V, frequencies are kept 10 MHz. The area ratio is kept at 21%. The phase of RF applied to electrode 1 is 0. The 0 and \( 2\pi \) cases are set as a reference both in (d1) and (d2). The plasma density curves above electrode 1 rise with the phase-shift increase from 0 to \( \pi \) and the peaks move to the electrode 2 direction gradually in Fig. 3(d1), and the tails of the curves lay below the 0 curve. The main curves above electrode 2 fall with the phase-shift increases from \( \pi \) to \( 2\pi \) and the peaks slowly move to the center of electrode 2 in Fig. 3(d2). The tails of curves are higher than the \( 2\pi \) curve except for the \( \pi \) and \( 1.25\pi \) curves. 0 and \( \pi \) curves are boundaries of the curves space. Phase-shifts can effectively affect the shape of the plasma density curve and the corresponding non-uniformity.

4.2.2 Non-uniformity of \( n_e \)

The non-uniformity of \( n_e \) with different electrode area ratios are shown in Fig. 4(a). Area2 and AreaT denote the area of electrode 2 and the total area, respectively. The curve has a valley shape. The valley point of non-uniformity is reached at area ratio 21%. The non-uniformity decreases with the ratio increases from 0 to 0.21 and increases with the ratio increases to 0.75. The minimal non-uniformity at area ratio 21% is 56.5% of the original case.

The non-uniformity of \( n_e \) with different electrode 2 voltages is shown in Fig. 4(b). Same with the electrode area curve, the voltage curve also has a valley shape. The valley point of non-uniformity is reached at the configuration of electrode 2 voltage increment 12%. Non-uniformity decreases with the voltage increase from 0% to 12% and increases with the voltage increase to 18%. The minimal non-uniformity at voltage increment 12% is 53.5% of the original case.

The non-uniformity of \( n_e \) with different electrode 2 frequencies is shown in Fig. 4(c). The frequency curve is almost a linear function. The non-uniformity curve is monotone increasing, which means that the lowest point reached at \( f_2 \) equals \( f_1 \). Any frequency bigger than \( f_1 \) deteriorates the non-uniformity of plasma density. All non-uniformities are bigger than the original case.

The non-uniformity of \( n_e \) with different electrode 2 phase-shifts is shown in Fig. 4(d). The phase-shift curve is a periodical function. The peak point is achieved at phase \( \pi \), but the valley point is got at 1.85\( \pi \) not 0. It is found that most phase-shifts only deteriorates the non-uniformity of plasma density except a special window of 1.75\( \pi \) to 2\( \pi \) which is one-eighth of 2\( \pi \). The minimal non-uniformity at 1.85\( \pi \) is 72.3% of the original case.

![Fig.4 Non-uniformity of plasma density with (a) different area ratios from 0% to 75%, (b) Voltages from 0% to 18%, (c) Frequencies from 0% to 0.5%, (d) Phase-shifts from 0 to 2\( \pi \)](image)

4.2.3 Path of \( n_e \) peak

The non-uniformity is affected by the distribution of plasma density, in other words, the shape of the curve is mainly affected by the peak and valley points values and positions. The valley point is usually at the tail of the curve (0 position). The peak positions are not fixed. The path of the plasma density peak at the probe line is tracked and recorded.

The path of plasma density peak affected by electrode area is shown in Fig. 5(a). The plasma density peak is near the center of the chamber at area ratio 0% and 8%, which is far from the electrodes interface. With a small slope, the peak moves to the interface at area ratio 19%. With the increase of area ratio from 19% to 75%, the peak moves to the left following the interface and the slopes of path curve change from steep to smooth.
The path of plasma density peak affected by voltage is shown in Fig. 5(b). The plasma density peak moves towards the right with the increment of voltage from 0% to 6%, which is mainly in the plasma above electrode 1. The peak of voltage increment from 9% to 18% stays in the same position above electrode 2. The peak position is not affected by the increment of voltage since 9% when the area of electrode 2 is fixed and the peaks are on the right side of the electrode interface.

Fig.5 Path of plasma density peak with (a) area ratios from 0% to 75%, (b) voltage increment of electrode 2 from 0% to 18%, (c) frequency increment of electrode 2 from 0% to 0.5%, (d) phase-shifts from 0 to 2π

The path of plasma density peak affected by frequency is shown in Fig. 5(c). The plasma density peak moves towards the right with the increment of frequency from 0% to 0.5%, which is mainly in plasma above electrode 1. The slope of curve increases faster since +0.05%. The peak path is similar to the path of the voltage except for the fixed position part. The peak position of +0.5% is on the left side of the electrode interface.

The path of plasma density peak affected by phase shift is shown in Fig. 5(d). The peak cycles and the path is closed at 0/2π. The plasma density peak moves towards the right with the increment of phase from 0 to π, which is mainly in the plasma above electrode 1, and the shape of the curve is similar to the paths of frequency. The slope of the curve increases faster since 0.15π. The peak path achieves peak at phase π, which is on the left side of the electrode interface. The plasma density peak falls with a steep slope from π to 1.85π and moves towards the left to close the curve. The peak curve comes across the electrode interface line and is mainly above electrode 2. The main part of the peak curve stays around the interface line.

The curve from 0 to π and the curve from π to 2π are on both sides of the electrode interface, which is similar with the combination of peak curves affected by frequencies and voltages. Tuning the proper phase-shift obtains the same trace as frequency or voltage.

The peak curves affected by area ratio/voltage/frequency/phase-shift stay around the electrode interface indicates big energy deposition density excited by the superposition of the electric field at this area.

5 Conclusion

Lowering the non-uniformity of plasma density is needed to improve the yield of IC chip manufacture. The configuration of two parallel plates is typical for a traditional CCP discharge. One plate electrode is connected to RF sources and another is grounded. The plate electrode can be applied with single frequency or dual-frequency RF sources. The electromagnetic field is stimulated as one from one region (electrode) with one or more RF sources in parallel plates, while dual-electrodes split the region with different RF sources. Splitting one electrode into n pieces offers the flexibility of fine tuning to lower the non-uniformity of plasma density.

Dual electrodes configuration is discussed here to investigate the non-uniformity affected by parameters such as electrodes area, RF voltage, frequency and phase shift. A traditional fluid plasma model is adopted and only argon ionization is considered in numerical simulations.

Electrode area ratio, RF voltage, frequency and phase-shift have the relationship with plasma density which are useful for improving uniformity. With the splitting of the electrode region, increasing RF voltage and electrode area ratio has a non-monotonic effect on the non-uniformity, while increasing RF frequency deteriorates the non-uniformity monotonically. The non-uniformity induced by the phase-shift has a cyclical variation. The original non-uniformity is reduced by 46.5% at a voltage increment of 12%, frequency 10 MHz, area ratio 11%, and phase shift zero in the studied cases. Dual-electrode or multi-electrode is an effective method to reduce the non-uniformity.

The path of plasma density peak has been tracked in this study and the peak moves around the electrode interface. A properly tuning phase-shift is found that can achieve the same peak trace as tuning frequency or voltage.

References
