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2012 Plasma Sources Sci. Technol. 21 035018

(http://iopscience.iop.org/0963-0252/21/3/035018)

Plasma Sources Sci. Technol. **21** (2012) 035018 (5pp) doi:10.1088/0963-0252/21/3/035018

Synergetic effects in a discharge produced by a dual frequency–dual antenna large-area ICP source

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Received 31 October 2011, in final form 27 March 2012
Published 29 May 2012
Online at stacks.iop.org/PSST/21/035018

Abstract
Using an RF-compensated Langmuir probe, plasma parameters have been investigated in a discharge produced by a dual frequency–dual antenna: the next generation of large-area inductively coupled plasma (ICP) sources. The ICP source was made of two concentric spiral copper coils embedded into each other. The inner and outer coils were energized by RF frequencies of 2 and 13.56 MHz, respectively.

The discharge was operated at an average pressure of 10 mTorr in an argon gas environment. The probe was positioned at a fixed location of 70 mm from the source and 160 mm from the centre of the ICP source to measure the plasma parameters. However, for discharge uniformity measurements, the probe position was varied from the centre of the discharge to 200 mm towards the edge.

It was found that the ion density distribution over the wafer varies with RF power ratio ($P_{2\,\mathrm{MHz}}/P_{13.56\,\mathrm{MHz}}$). For a fixed power at 13.56 MHz ($P_{13.56\,\mathrm{MHz}}$), the plasma density increases very slowly with $P_{2\,\mathrm{MHz}}$, when $P_{2\,\mathrm{MHz}} < 400$ W; however, the plasma density increases rapidly when $P_{2\,\mathrm{MHz}} > 400$ W. The electron temperature and plasma potential measurements show decreasing trends with increasing $P_{2\,\mathrm{MHz}}$ at constant $P_{13.56\,\mathrm{MHz}}$. The ion density measurements over the substrate show that good discharge uniformity (∼4%) can be achieved by adjusting the RF power ratio ($P_{2\,\mathrm{MHz}}/P_{13.56\,\mathrm{MHz}}$).

1. Introduction

Plasma processing is extensively used in the micro-electronics industry for manufacturing various electronic devices such as semiconductor appliances, thin film transistors and liquid crystal displays [1–3]. Currently, the semiconductor industry aims to achieve the fabrication of electronic devices at the level of a few tens of nanometres. However, the fabrication cost increases as the size of the electronic device reduces. Therefore, a large-area wafer size is necessary in order to improve productivity and optimize the fabrication costs of such micro-electronic devices. This gives an impetus for the development of large-area plasma sources for the next generation of micro-electronic devices. According to a technology trend forecast, the wafer size will be 450 mm in diameter within a few years [4, 5].

The most significant challenge for fabrication on a large-area wafer size is to precisely control the distribution of the plasma species over the substrate. Over the last decade, many types of high-density and large-area plasma sources, based on using different mechanisms of power coupling to discharge and geometrical configurations, have been extensively investigated for large-scale semiconductor processing. Various ideas, such as segmented and gridded antennas, together with capacitively coupled plasmas (CCPs) [6], have been proposed and implemented to reduce the standing wave effect. An improved radial uniformity has been demonstrated by using a C-type ferrite enhancement in inductively coupled plasmas (ICPs) [7]. Various other configurations of plasma sources, such as CCPs, very high frequency capacitively coupled plasmas (VHF-CCPs) and ICPs (ferrite core assisted and dual comb type antennas), have been proposed and investigated [8–15]. Distributed helicon sources, electron cyclotron resonance (ECR) and surface wave excited plasma sources have also been investigated [16] in order to achieve large-area plasma sources with enhanced discharge uniformity over the substrate.

Among all of the plasma sources, the CCP sources operating at 13.56 MHz were the first to be adopted by the plasma processing industry. Anisotropic etching at the sub-micron level requires an ion collisionless sheath in front of the substrate, which can be achieved while operating the discharge at a low pressure (<10 mTorr). However, CCP sources are not able to drive discharges at low pressures (<10 mTorr), due to the weak RF power coupling to the discharge through the sheaths. Operating the CCP sources at very high frequencies (typically 2–10 times higher than 13.56 MHz) was proposed in order to drive these discharges at low pressures (<10 mTorr) [17, 18]. However, when the radial dimension of the substrate (R) is comparable to the wavelength of the operating frequency ($R \sim \lambda_0$), a standing wave develops in the discharge and produces the strong discharge non-uniformity over the substrate area. Using experimental [19] and computational techniques, it has been demonstrated that the introduction of phase difference (electrical asymmetry) between the RF powers applied at the top and bottom electrodes could be utilized to control the plasma non-uniformity in very high frequency CCP discharges [19, 20]. However, being able to operate at low pressures (due to the strong power coupling through the electromagnetic field, a high density plasma, easier plasma uniformity control, and the separation of discharge production and ion acceleration mechanisms of the ICP sources) turned the research direction towards developing and investigating ICP sources for the fabrication of large-area micro-electronic devices.

ICP sources are potential candidates for large-area fabrication due to their low pressure operation (<10 mTorr) and high plasma density characteristics. However, scaling up conventional ICP sources poses some problems, such as increased antenna impedance which, in turn, increases the RF voltage drop across the antenna and, therefore, decreases the average power transfer efficiency to the discharge and azimuthal non-uniformity, which is due to the standing wave effect. When the substrate is comparable to the wavelength of excitation radio frequency ($\lambda_0 \sim R$), where λ_0 is the free space wavelength and R is the substrate's radius, a standing wave develops in the discharge and produces strong azimuthal non-uniformity in reactants in flux over the substrate. The standing wave effect could be avoided by using a lower excitation frequency ($\lambda_0 > R$). However, the power absorption efficiency decreases with decreasing excitation frequency; therefore, it is hard to ignite the discharge at the low excitation frequency. Therefore, it is speculated that a discharge produced by a combination of two excitation frequencies (13.56 MHz for ignition of the discharge and 2 MHz for driving the discharge's body) applied at two different coils embedded into each other may be a potential solution to the strong discharge non-uniformity observed in large area plasma sources.

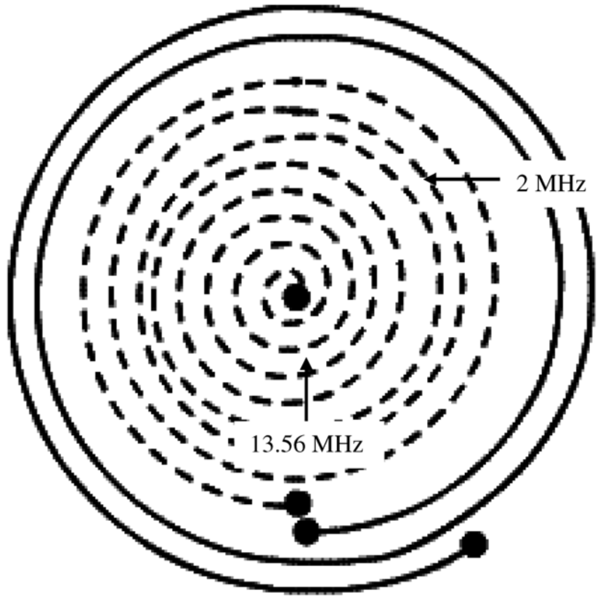

Figure 1. Schematic of dual frequency inductively coupled antenna. The inner coil (shown by a broken line) was used to feed 2 MHz RF power, whereas the outer coil (shown as a solid line) was fed by 13.56 MHz RF power.

The present study reports the investigation of the electrical parameters of a discharge produced by a dual antenna–dual frequency large-area ICP source, excited by two frequencies of 2 and 13.56 MHz, and the operating conditions to obtain discharge uniformity over the substrate area.

2. Experimental set-up

The schematic of the dual antenna–dual frequency ICP source is shown in figure 1. It consists of two planar-spiral coils made of a copper tube, 7 mm in diameter. The inner coil has 12 turns and a diameter of 320 mm, and the outer coil has 3 turns. The RF powers at 2 and 13.56 MHz are fed to the inner and outer coils via two separate matching networks.

The schematic of the experimental set-up and the acquisition instrumentation is shown in figure 2. The argon discharge was operated in a cylindrical anodized aluminium chamber using an external type dual antenna–dual frequency ICP source, which was separated from the main processing chamber by a dielectric window. The chamber walls were electrically grounded. The argon gas in the chamber was evenly distributed by a multi-holed shower ring, located near the periphery of the chamber. The pressure inside the chamber was controlled with a mass flow controller (2900 series, Tylan) together with an adaptive pressure controller (PM-7, VAT) for the gate's valve control. The inner and outer coils were energized by 2 MHz (NOVA-50 A, ENI) and 13.56 MHz (CX-5000S, COMDEL) RF power supplies, respectively, via an automatic matching network. The operating pressure was kept at 10 mTorr. The RF power

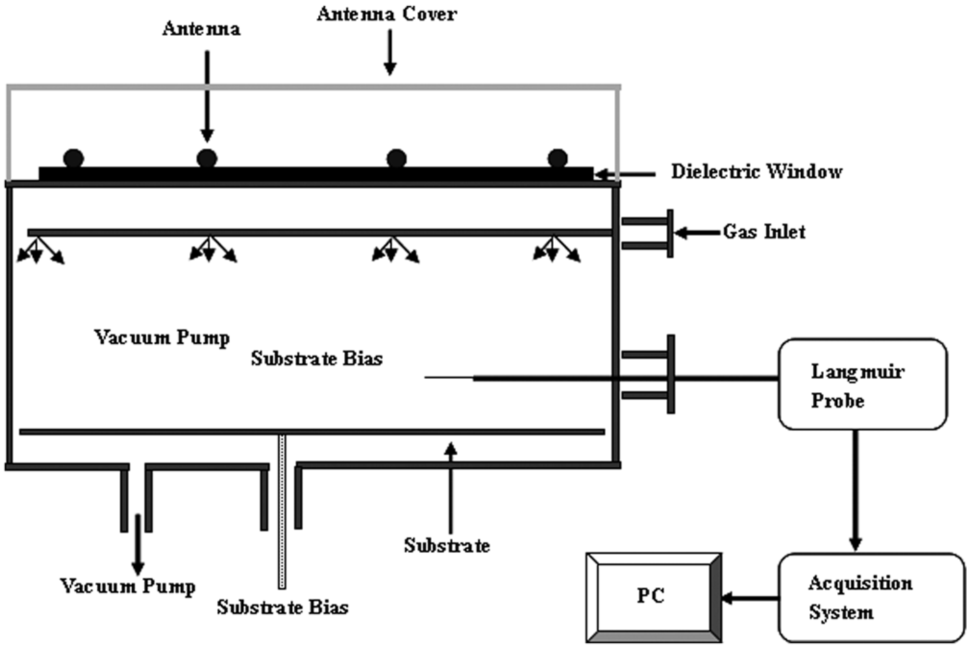

Figure 2. Schematic diagram of the experimental set-up with data acquisition arrangement. The Langmuir probe was located at 70 mm below the antenna (near substrate region) and 60 mm away from the centre of the antenna.

variation was 100–800 W and 0–1000 W for 2 and 13.56 MHz, respectively.

The plasma parameters, such as plasma density, electron temperature and plasma potential, were measured using an ESPion Langmuir probe system supplied by Hiden Analytical Ltd., UK. An RF compensation unit was used together with the Langmuir probe to prevent the RF incursion on the probe sheath's potential, which distorts I–V characteristics [21–23]. The probe's tip was made of tungsten, 0.15 mm in diameter and 10 mm in length. To minimize the random noise in the I–V characteristics, a single I–V characteristic scan was acquired by sampling a single point 10 times and then the 10 scans were averaged to get one final scan.

3. Results and discussion

3.1. Measurement of discharge parameters

Figure 3 shows the electron density (n_e) variation in the plasma with $P_{2\,\text{MHz}}$. The Langmuir probe was located at 70 mm (near the substrate region) below the ICP source and 60 mm away from the centre of the chamber. For this set of experiments, the $P_{\text{av}13.56\,\text{MHz}}$ was fixed at three chosen values of 0, 500 and 1000 W. In this experimental study, stable discharges could not be achieved at $P_{2\,\text{MHz}} < 500$ W when $P_{13.56\,\text{MHz}}$ was not applied. Sometimes the discharge could be ignited while on other occasions it was extinguished and was not operational. Therefore, it was not possible to get accurate measurements that reflected the discharge properties at this operational condition. That is the reason why there are no measurements shown in the plots in this operational regime ($P_{2\,\text{MHz}} < 500$ W and $P_{13.56\,\text{MHz}} = 0$). In addition, when $P_{2\,\text{MHz}}$ was less than 500 W, the plasma density (n_e) was almost the same, irrespective of any chosen value of $P_{13.56\,\text{MHz}}$.

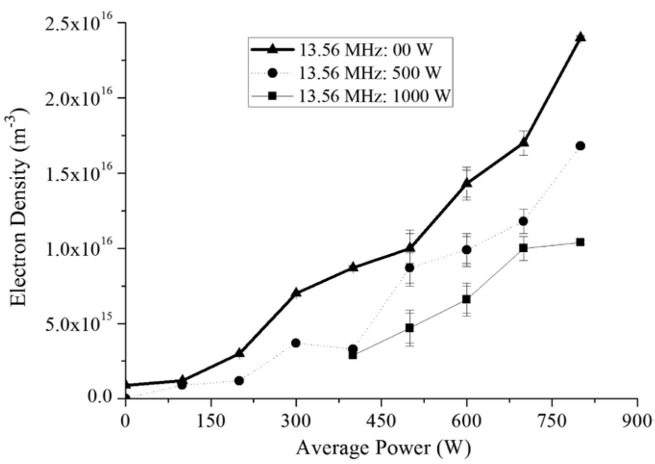

Figure 3. Electron density variation in the plasma with 2 MHz RF power for three different 13.56 MHz RF powers.

The reason for this observation is that the Langmuir probe was located away (about 120 mm) from the 13.56 MHz coil; therefore, the n_e at the probe's location was not significantly affected by any change in $P_{13.56\,\text{MHz}}$. The slight variation observed in n_e (at $P_{2\,\text{MHz}} < 500$ W) may be due to the combined effect of the change in $P_{2\,\text{MHz}}$, $P_{13.56\,\text{MHz}}$ and an error associated with the Langmuir measurements.

For $P_{2\,\text{MHz}} > 500$ W, n_e increases almost linearly with power at all chosen values of $P_{13.56\,\text{MHz}}$. This observed increase in n_e with $P_{2\,\text{MHz}}$ and $P_{13.56\,\text{MHz}}$ is quite obvious as the increased RF power results in more power coupled to the discharge which, in turn, increases the ionization and therefore produces higher n_e. The ionization processes in the plasma become more effective with increased power; multi-step ionization might come into play [25–27]. The electron density increases by almost 5 times by increasing $P_{2\,\text{MHz}}$ from 300 to 800 W at 1000 W of $P_{13.56\,\text{MHz}}$.

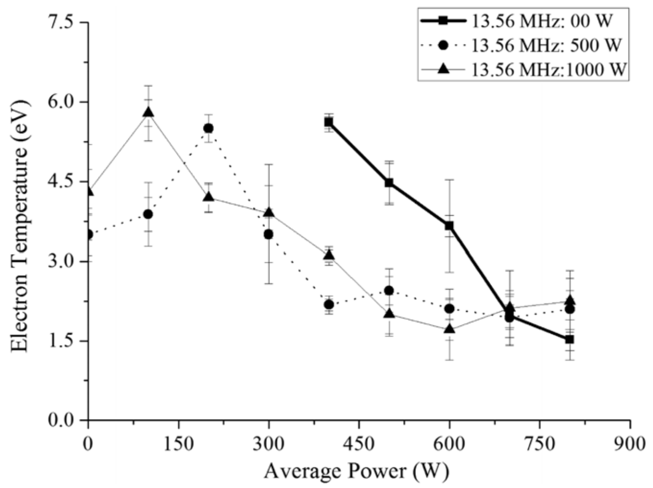

Figure 4. Electron temperature variation with 2 MHz RF power for three different 13.56 MHz RF powers.

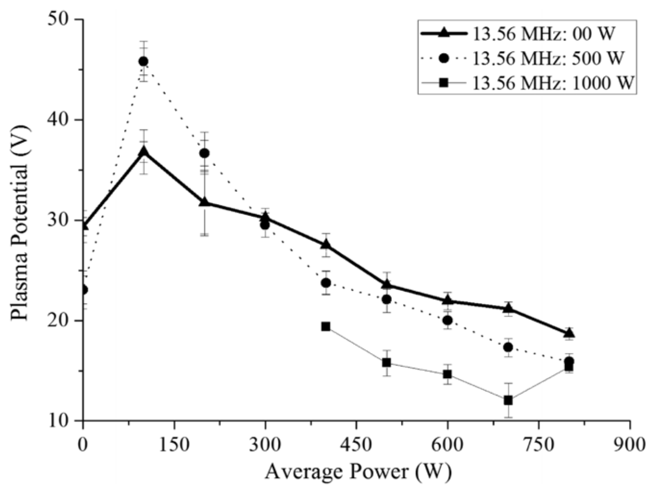

Figure 5. Plasma potential variation with 2 MHz RF power for three different 13.56 MHz RF powers.

Figure 4 shows the variation of the electron temperature (T_e) with $P_{2\,MHz}$ and $P_{13.56\,MHz}$. As can be seen, T_e initially increases by a few eV, when $P_{2\,MHz}$ is applied to the inner coil. After that, it decreases with increasing $P_{2\,MHz}$. T_e also decreases with increasing $P_{13.56\,MHz}$. The decreasing trend of electron temperature with power is common to glow discharge plasmas and may be attributed to two-step ionization, which increases with plasma density and which, in turn, reduces the electron temperature [26].

The plasma potential (V_p) variation with RF power is shown in figure 5. As shown, V_p decreases with increasing $P_{2\,MHz}$ when $P_{2\,MHz} > 100$ W; this could possibly be due to the decrease of T_e with increasing RF power. However, the increase of V_p with the increase of $P_{13.56\,MHz}$ at a fixed value of $P_{2\,MHz}$ even with the decrease of T_e appears to be related to the increased potential on the outer coil (increased sheath potential by capacitive coupling) with increasing $P_{13.56\,MHz}$. The jump in V_p, as well as in T_e, was observed when $P_{2\,MHz}$ was introduced near 100 W; this observation might be related to the interaction of both frequencies, resulting in the electrons heating up.

3.2. *Measurement of ion flux uniformity*

In large-area plasma sources the most challenging issue is to maintain an etching uniformity over the substrate's surface; this is directly dependent on the ion flux distribution over the substrate. Therefore, an experimental study was carried out to measure the radial distribution of the discharge ion density over the substrate area. The substrate, probe location, measurement area and regions of the 2 and 13.56 MHz antennas are shown in figure 6. These measurements were carried out at a pressure of 10 m Torr and at a power of 800 W at 13.56 MHz. The average power at 2 MHz was varied from 0 to 400 W with a step of 100 W. In the figure, the probe's position was from 0–200 mm, that is, it scanned from the near edge of the discharge to centre of the discharge.

In interpreting the experimental results, the term 'discharge non-uniformity' is used and is defined as the percentage difference between maximum and minimum plasma density $((n_{e\,max} - n_{e\,min}/n_{e\,max}) \times 100)$, where $n_{e\,max}$ and $n_{e\,min}$ are the maximum and minimum plasma densities. It can also be seen from figure 6 that the uniformity of the discharge over the substrate was poor (non-uniformity = 23%) when $P_{2\,MHz}$ was zero: there is no discharge formed at the centre of the chamber and the discharge is generated only at the circumference of the chamber where the antenna, excited by 13.56 MHz, is situated. Therefore, the discharge diffuses towards the centre of chamber and it produces a negative plasma density gradient towards the centre of the discharge, which is the origin of this observed non-uniform discharge. However, as $P_{2\,MHz}$ is increased, the discharge uniformity over the substrate also improves. As $P_{2\,MHz}$ is applied, the discharge is also formed at the central part of the chamber and this results in an increase in the uniformity. However, when $P_{2\,MHz}$ is higher than 300 W, the uniformity again decreases due to the unbalance between the ion density profiles from the outer 13.56 MHz coil and the 2 MHz coil. Therefore, by balancing the RF powers between the outer 13.56 MHz and the inner 2 MHz coil, a uniform ion density profile over the large area substrate can be maintained. Based on the above observations, we speculate that the discharge non-uniformity observed in the substrate's outer region which is covered by the 13.56 MHz antenna could be reduced significantly by covering whole of the substrate area by the 2 MHz antenna and reducing the area covered by the 13.56 MHz antenna, i.e. reducing the number of turns in the antenna used for 13.56 MHz or placing it outside the substrate region.

4. Concluding remarks

Using an RF-compensated Langmuir probe, the discharge characteristics of plasmas produced by a dual frequency–dual antenna (DFDA) ICP source, having two concentric planar RF coils, have been investigated. The electron density n_e increases with RF power at both frequencies. This increasing power dependence of the electron density is typical in ICP glow discharge plasmas and is caused by multi-step ionization. The electron temperature T_e decreases with the increase of both RF powers while the plasma potential increases with an

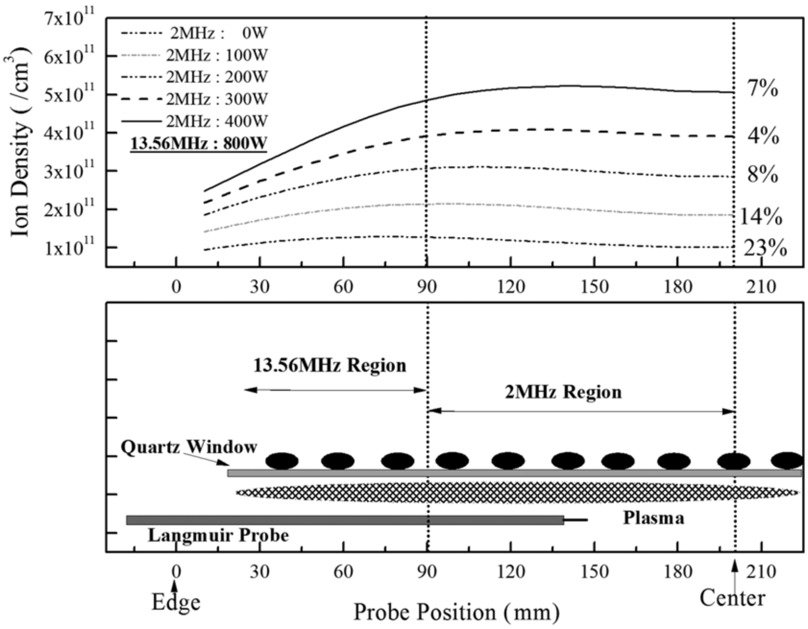

Figure 6. Ion flux density distribution over the substrate surface area and a schematic of Langmuir probe measurement region.

increase of the 13.56 MHz RF power. It was observed that the plasma potential decreases with an increase of the 2 MHz RF power. This falling electron temperature dependence on both RF powers is the result of an increased plasma density due to multi-step ionization which, in turn, reduces the electron temperature. The ion flux density, measured over the surface area of the substrate, demonstrates how the balance of the RF powers from two concentric ICP sources plays a vital role in achieving discharge uniformity.

Acknowledgments

This work was supported by the IT R&D Program of MKE (2009-S-007-1, development of 300 mm wafer backend processing equipment for 32 nm node semiconductor devices). This work was also supported in part by the World Class University program of the National Research Foundation of Korea (Grant No R32-2008-000-10124-0) and by the Ministry of Education, Science and Technology (2010-0015035).

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