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Improving discharge uniformity of industrial-scale very high frequency plasma sources by launching a traveling wave

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ABSTRACT

Very high frequency (VHF) PECVD has been demonstrated to be able to significantly increase the deposition rate without compromising the film quality for the manufacture of silicon heterojunction and silicon thin film solar cells. To further reduce the production costs by enhancing the throughput, larger electrode and higher frequency are often required at the same time. Nevertheless, raising frequency in large-area PECVD results in non-uniform discharge caused by the standing wave effect and deteriorates the processing uniformity. In this study, a technique that generates a traveling wave via superposing two specific standing waves launched simultaneously is proposed to resolve this issue. An industrial-scale linear plasma reactor with length and width of 125 and 10 cm, respectively, is adopted for experimental tests and two 80 MHz power supplies are utilized to separately control the standing waves. The experimental results show that the discharge gap is only partially covered by plasma discharge when only one standing wave is applied. However, as both standing waves are launched, the non-uniformity of plasma discharge can be effectively reduced to $<\pm5\%$. In addition, numerical simulation is also conducted in this study to clarify whether the proposed technique can be applied to large-area rectangular PECVD (substrate size: 1.4 m × 1.1 m). By arranging multiple feeding points on opposite sides of the powered electrode, the simulation results indicate the non-uniformity of electric field can be maintained within $\pm10\%$.

1. Introduction

Plasma-enhanced chemical vapor deposition (PECVD) has been successfully integrated into the manufacturing processes for varieties of industries, such as semi-conductor, flat-display panel and solar cell, for a few decades. The typical plasma source of PECVD comprising parallel planar electrodes, known as capacitively coupled plasma (CCP), has been conventionally operated at 13.56 MHz. In order to reduce the production costs by enhancing throughput, the improvement in deposition rate is always an important issue for industrial applications. Generally, however, this task cannot by fulfilled by simply raising the discharge power because such a measure would lead to higher ion bombardment energy as well due to the capacitive nature of CCP. Consequently, the increase in deposition rate at higher discharge power is inevitably achieved with deteriorated film quality, which is the reason why VHF (very high frequency, 30–300 MHz) CCP has received considerable attention over the past decade.

With the characteristics of higher electron density [1–5] and lower sheath voltage [6–10] under a constant discharge power, VHF PECVD has proved to be effective in improving the deposition rate while maintaining or even improving the film quality for the manufacture of silicon heterojunction [11,12] and silicon thin film solar cells [5,6,13–16]. However, the aforementioned advantages of VHF CCP come with the drawback of substantial electromagnetic effects posing serious problems for processing uniformity. The important electromagnetic effects include the standing wave and skin effects, which would play an important role in determining the discharge pattern when the electrode dimensions are smaller than 1/10 of vacuum wavelength and when the plasma skin depth is comparable to the discharge gap, respectively [17,18]. When it comes to PECVD, which is typically operated at power density one to two order of magnitude lower than that of etching processes, the

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skin effect can often be ignored because the electron density is lower and hence the decay of electromagnetic wave while propagating through the bulk plasma is insignificant [19]. As a result, the standing wave is the dominating electromagnetic effect in large-area VHF PECVD.

In order to solve the problem of non-uniform discharge induced by the standing wave effect, the authors have proposed a technique based on the concept of generating a traveling wave by launching two specific standing waves at the same time and preliminarily demonstrated its feasibility for linear plasma reactor, in which one dimension of the electrodes is much longer than the other, via numerical simulation [20]. According to the simulation results, the generation of traveling wave can be described by either of the following equations:

$$A \times \cos(\omega t) \times \cos(-kz) + A \times \cos(\omega t \pm 90^{o}) \times \cos(-kz \mp 90^{o}) = A \times \cos(\omega t - kz) \tag{1}$$

$$A \times \cos(\omega t) \times \cos(-kz) + A \times \cos(\omega t \pm 90^{o}) \times \cos(-kz \pm 90^{o}) = A \times \cos(\omega t + kz) \tag{2}$$

where A is the amplitude of voltage, ω is the angular frequency, t is time, k is the phase constant and z is the distance along the direction of wave propagation. The LHS of Equations (1) and (2) represents two individual standing waves while the RHS, i.e., the linear superposition of the applied standing waves, is clearly a form of traveling wave. The only difference between Equations (1) and (2) is the moving directions of the resulting traveling waves. According to these equations, it can be concluded that three essential conditions must be fulfilled for the applied standing waves to produce a traveling wave, namely, both the spatial and temporal phase differences (denoted as φ_s and φ_t, respectively) between the standing waves have to be 90° and the amplitudes must be the same.

The present work is divided into two parts. The first part attempts to further verify the viability of the proposed technique through experimental tests using an industrial-scale linear plasma reactor. In the second part, the numerical simulation is further extended to large-area rectangular PECVD with the aim to demonstrate the proposed technique is also capable of effectively improving the discharge uniformity in large-area rectangular VHF plasma source.

2. Experiments

The experimental setup is schematically shown in Fig. 1. An industrial-scale linear plasma reactor was utilized to demonstrate the viability of generating a traveling wave by launching two specific standing waves simultaneously to solve the problem of non-uniform discharge caused by the standing wave effect. The electrodes were 125 cm in length and 10 cm in width. The discharge gap was 1.7 cm. Each end of the upper electrode was connected with a 2-way power combiner mounted on the chamber wall, providing four feeding points outside the reactor. The lower electrode was grounded at the center.

Two 80 MHz power supplies both connected to a 2-way power divider were employed to independently control two standing waves with different discharge patterns. The electromagnetic waves from the same power supply were introduced into the plasma reactor on opposite sides of the powered electrode. The phase difference between the input electromagnetic waves from the same power source is represented by θ. As mentioned previously, in order for the superposition of the applied standing waves to behave as a traveling wave, φ_s and φ_t must both be 90° and the amplitudes should be the same. In this study, φ_s, φ_t and amplitudes are controlled via different measures. First of all, it is well known that locations of anti-nodes and nodes of a standing wave depend on the phase difference between the electromagnetic waves propagating in opposite directions, i.e., θ, which can be changed by varying the cable lengths connected to the opposite ends of plasma reactor. As shown in Fig. 1, the cable lengths are designed to ensure θ for the first and second power supplies are 0° and 180°, respectively. In this manner, the former would generate a standing wave with an anti-node at the center of electrode while a node is located at the same location for the latter. When the anti-node of a standing wave is aligned with the node of another, it physically means that these two standing waves is out of phase by 90° in space, suggesting the requirement for φ_s is already met using the experimental setup shown in Fig. 1. For simplicity, the standing waves with θ of 0° and 180° are termed as the first and second standing waves, respectively. Furthermore, the power supplies were synchronized through CEX (common exciter) interface, allowing the alteration of the phase difference between their output signals, i.e., φ_t. Finally, the amplitude of each standing wave depends on the output power of the corresponding power supply.

All the experimental tests were conducted using Ar as plasma gas. The plasma gas was introduced into the discharge gap via a lateral gas distributor. The pressure and power density tested in this study ranged from 0.2 to 0.6 Torr and from 0.04 to 0.08 W/cm^2, respectively. The power supplies were always operated without reflected power when either only one standing wave or both standing waves were ignited. The non-uniformity of plasma discharge is determined by the ion density (n_i) profile measured by Langmuir probe. The measurements were taken in the mid gap along the length of the electrodes. The data of ion density presented in this study are the average of at least 3 measurements. The definition of non-uniformity is given below:

$$\text{Non} - \text{uniformity} = \frac{\text{Max.}\ n_i - \text{Min.}\ n_i}{\text{Max.}\ n_i + \text{Min.}\ n_i} \tag{3}$$

3. Results and discussion

3.1. Experimental verification of uniform discharge for industrial-scale linear plasma reactor

Fig. 2(a) and (b) display the photos of plasma discharges for the first and second standing waves, respectively. The results show that the standing wave pattern is a function of the phase difference between the electromagnetic waves fed into the reactor on opposite sides, i.e., θ. When the electromagnetic waves are in phase, that is, $\theta = 0°$, an anti-node is observed at the center of electrode because of constructive inference. On the contrary, destructive inference takes place at the same position instead when θ is changed from 0° to 180°, leading to the formation of a node. It should be noted that if θ is between 0° and 180°, neither the anti-node nor the node is located at the center but the anti-node and node would move towards the center of electrode when θ is closer to 0° and 180°, respectively, which has been confirmed by various studies [21–23]. On the other hand, the interval between an anti-node and an adjacent node corresponds to a quarter wavelength. Accordingly, it can be concluded that φ_s between the first and second standing waves is 90° based on the results shown in Fig. 2.