Characteristic of VHF plasma produced by balanced power feeding

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Abstract. The characteristics of a VHF hydrogen plasma produced by a balanced power feeding method were examined using a two-dimensional hybrid model. The simulation results showed that the electron density peaks at a certain pressure inside the discharge electrodes and significantly decreases outside the electrodes for high gas pressure. In addition, the power absorption efficiency inside the electrodes was improved by increasing the gas pressure. On the other hand, the plasma was produced within the electrodes for low applied voltages.

1. Introduction

The production of a VHF discharge plasma with large area at high pressure is one of the key technologies in the fabrication of thin-film silicon solar cells because VHF discharge plasma provides high-rate film deposition with low electron temperature [1]. However, in this type of discharge, anomalous discharges occur outside the discharge electrodes. The anomalous discharges consume a large amount of the input power and cause unstable discharges inside the electrodes. Moreover, the anomalous discharges damage components around them, for example a power feeding cable, as the result, the film is contaminated with the sputtered materials. Thus, the occurrence of the anomalous discharges must be avoided for large area and qualified solar cells.

As one of the techniques to avoid the occurrence of the anomalous discharges, a balanced power feeding (BPF) method has been proposed [2]. Nishimiya et al. [2] demonstrated that this method successfully suppresses anomalous discharges and the electron density is higher than that without BPF.

We have studied the VHF plasma produced by the BPF method for effective application to the PECVD. In our previous work [3], we calculated the VHF hydrogen plasma produced by the BPF method, in which we focused on the effects of the VHF voltages applied to each electrode with same amplitude and opposite signs. We confirmed that the BPF method improved the VHF hydrogen plasma characteristics with short-gap parallel plate electrodes: the electron density outside the electrodes significantly decreased and the electron density and the absorbed power increased inside the electrodes compared to those in the conventional single-electrode power feeding (SPF) model. Thus, the advantage of the BPF method was shown in this preliminary work. In the present paper, we examined the characteristics of the VHF plasma produced by the BPF in detail, that is, the dependences on the gas pressure and on the amplitude of the VHF voltages which were applied to the both electrodes.

2. Description of the model

The simulation of a VHF plasma produced by the BPF method was performed by using the Plasma Hybrid Module (PHM) of PEGASUS software Inc.[4] The PHM has been developed on the basis of the Hybrid Plasma Equipment Model (HPEM) formed by Kushner and his colleagues [5]. The detailed description of the PHM is described in our previous paper [3]. Here, we briefly outline the computational procedure of the PHM. The density and the velocity of electrons, which are utilized for the calculation of the electron energy distribution functions (EEDFs) by Monte Carlo method, are calculated by the fluid model and the equation motion of electron. The density and the velocity of ions are determined by solving the equations of continuity in which the drift diffusion model is applied to the particle fluxes. For neutral particles, Navier-Stokes equation and the advective diffusion equation are derived. Some CCP models, which were demonstrated by Lymberopoulos and Economou [6] and by Rauf and Kushner [7], were calculated by using the PHM, and the simulation results of PHM showed good agreements in the previous researches.

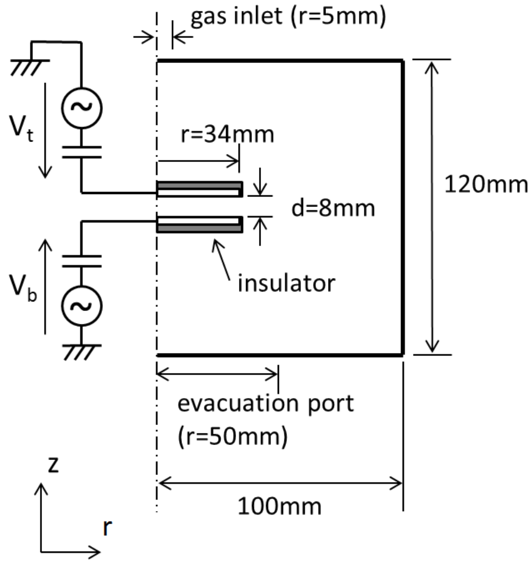

Figure 1. Schematic of the BPF model.

The BPF model we used here is a cylindrical coordinate system with axial symmetry, as shown in figure 1. A pair of parallel disk electrodes, whose radius is 34 mm, is situated in the center of a cylindrical chamber. The gap between the electrodes is fixed to 8 mm. The outside surfaces of the electrodes are covered with insulators, in order to suppress the emission of electric energy from them. In the BPF model, two VHF voltages V_t and V_b, whose amplitudes and phases are equal to and opposite from each other, are applied to the top and the bottom electrodes, respectively:

$$V_t = V_{rf}\sin(2\pi f t) + V_{dc,t},\ V_b = V_{rf}\sin(2\pi f t + \pi) + V_{dc,b}. \quad (1)$$

Here, V_{rf} and f are the amplitude and the frequency of the applied voltages, respectively. In this paper, f is fixed to 60 MHz. Self-bias voltages of each electrode $V_{dc,\,t}$ and $V_{dc,\,b}$ are included in the equations. The input power P_{elec} is defined as a time-averaged integral of the products of the applied voltages and the currents flow to the electrodes:

$$P_{elec} = P_t + P_b = \frac{1}{T_{rf}}\int_0^{T_{rf}} (V_t I_t(t) + V_b I_b(t))dt. \quad (2)$$

Here, T_{rf} is the time of a VHF cycle, and I_t and I_b are currents flow to the top and the bottom electrodes, respectively. The input power P_{elec} is equivalent to the total power absorbed in the calculating volume.

The hydrogen plasma in the model is consisted of electrons, H^+, H_2^+, H_3^+, H^-, H, H_2. The hydrogen gas is introduced with the flow rate of 300 sccm from the area around the center axis on the top face of the chamber. An evacuation port is located on the bottom face of the chamber. Here, the behavior of the leak currents is not considered in the model, so that, the effect of the applied VHF voltages in the BPF method on the VHF plasma with short-gap parallel electrodes was investigated.

3. Simulation results

1.1. Gas pressure dependence of BPF plasma

The gas pressure dependence ranging from 67 to 666 Pa was examined for V_{rf} = 100 V. In this operation, the input power was varied between 48 and 57 W. Figure 2 presents the pressure dependence of the electron density. As seen in figure 2 (a), the electron density outside the electrodes is significantly low when the gas pressure is higher than 200 Pa. This result indicates that the BPF method further suppresses the anomalous discharges for high pressures. On the other hand, the electron density inside the electrodes peaks at 400 Pa due to the electron trapping effect [8]. The same tendency was observed in the experiments of VHF hydrogen plasma produced by the BPF method [9]. When the gas pressure is higher than 400 Pa, the electron density in the center region between the electrodes becomes uniform with increasing the gas pressure, as seen in figure 2 (b).

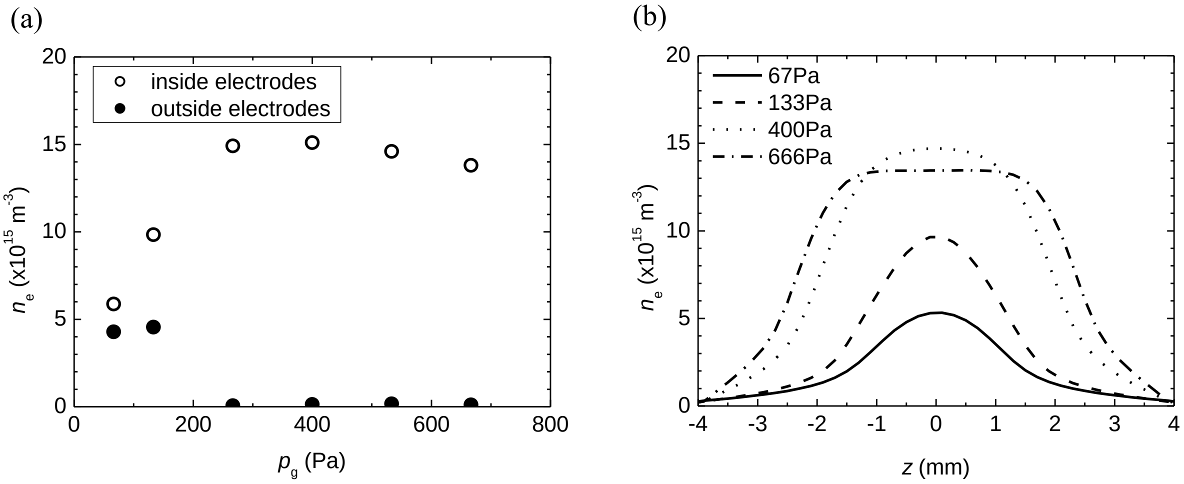

Figure 2. Characteristics of the electron density for different gas pressures at the applied voltage V_{rf} = 100 V: (a) pressure dependence of the peak electron density inside and outside the electrodes and (b) spatial distributions of the electron density between the electrodes in the *z*-direction at *r* = 20 mm.

Figure 3 shows the dependence of the absorbed power density P_{abs} inside the electrodes on the gas pressure. As shown in figure 3 (a), the power is more absorbed near the both electrodes due to the sheath heating [10]. As the gas pressure is increased, the absorbed power density increases in almost the whole region and takes a peak at $z = \pm 2.6$ mm. The enhancements of the power absorption in the sheath and in the middle region are due to the increases of stochastic heating proportionate to the increased electron density and of ohmic heating proportionate to the increased electron-neutral collision frequency, respectively. As shown in figure 3 (b), the total power absorbed inside the electrodes P_{in} also increases with increasing the gas pressure, and the absorption efficiency defined by P_{in} / P_{elec} reaches 87 % at p_g = 666 Pa. The reason for this tendency is because when the gas pressure is increased, the charged particles also increase inside the electrodes. These results indicate the BPF method is effective to supply the power into the process area for higher gas pressures.

The gas pressure dependence of the electron temperature is presented in figure 4. The electron temperature near the electrodes is about 2 times higher than that in the center region between the electrodes. From this result and figure 3 (a), the input power is used for heating of the electrons in the sheath region. The electron temperature decreases without changing its spatial profile when the gas pressure is increased. The low electron temperature is favorable for the production of the solar cell. The decrease of the electron temperature is due to the enhancement of the collisional quenching by neutral particles. On the other hand, the electron temperature outside the electrodes was almost constant around 0.8 eV.

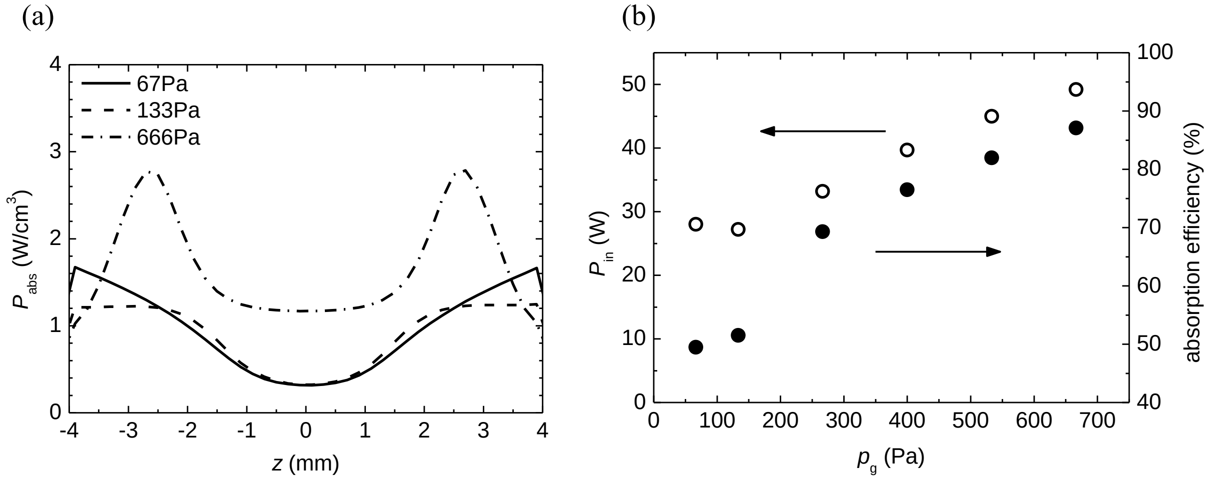

Figure 3. The characteristics of the power absorption for different gas pressures at the applied voltages of 100 V: (a) spatial distributions of the absorbed power density P_{abs} in the z direction at r = 20 mm and (b) the gas pressure dependence of the total power absorbed inside the electrodes P_{in} (open circles) and of the ratio of P_{in} to P_{elec} (closed circles).

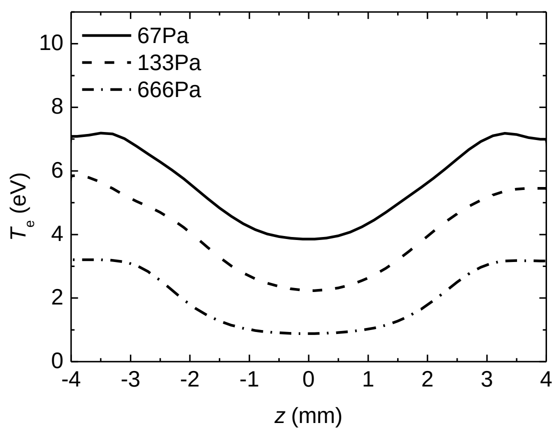

Figure 4. The spatial distributions of the electron temperature inside the electrode at r = 20 mm for different gas pressures. The applied VHF voltages are 100 V.

1.2. Applied voltage dependence of BPF plasma

The dependence of the BPF plasma on the applied voltages V_{rf} ranging from 80 to 150 V was obtained for the constant gas pressure of 133 Pa. In this operation, the input power was varied from 25 to 167 W with increasing the applied voltages. As shown in figure 5 (a), at the applied voltage of 80 V, the electron density inside the electrodes is one order of magnitude higher than that outside the electrodes. As the applied voltages are increased, the electron density increases both inside and outside the electrodes, and at V_{rf} = 150 V, the electron density outside the electrodes overcomes that inside the electrodes. However, it is noteworthy that the electrons outside the electrodes congregate adjacent to the reverse side of the electrodes. As seen in figure 5 (b), it is obvious that the electron density outside the electrodes in the BPF model rapidly decreases with the distance from the electrode compared to that in the SPF model, in which the same VHF voltage is applied to the top electrode and the bottom electrode is grounded. These results indicate that the supply of the VHF voltages with same amplitude and opposite sign to each electrode has an effect to limit discharge area in the vicinity of the electrodes.

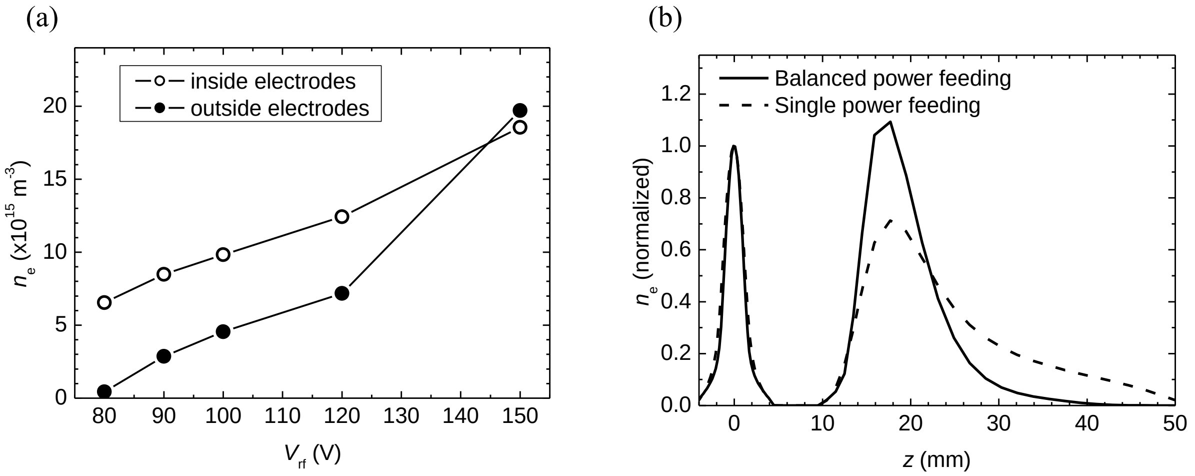

Figure 5. The characteristic of the electron density for the applied voltages for the gas pressure of 133 Pa: (a) the applied voltage dependence of the peak electron density inside the electrodes (open circles) and outside the electrodes (closed circles) and (b) spatial distributions of the normalized electron density in the BPF model (solid line) and the SPF model (dashed line) in z direction at r = 20 mm for the same applied VHF voltages of 150 V; $|z|$ < 4 mm: inside the electrodes; z > 10 mm: outside the electrodes.

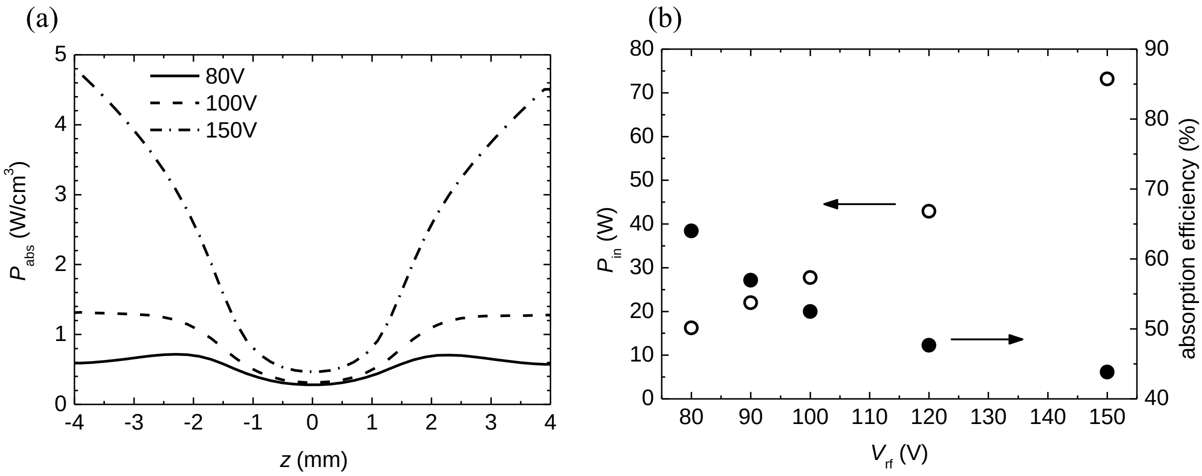

Figure 6. The characteristic of the power absorption for the applied voltages for the gas pressure of 133 Pa: (a) spatial distributions of the absorbed power density P_{abs} in z direction at r = 20 mm for the different applied voltages and (b) the applied voltage dependence of the total power absorbed inside the electrodes P_{in} (open circles) and the ratio of P_{in} to P_{elec} (closed circles).

As shown in figure 6 (a), the absorbed power density P_{abs} increases near the electrodes with increasing the applied voltages since the potential drop within the sheath becomes large, while the enhancement of P_{abs} in the center region between the electrodes is less than 0.2 W/cm^3. Figure 6 (b) indicates the total power absorbed inside the electrodes P_{in} increases as the applied voltage is increased.

However, the absorption efficiency decreases with increasing the applied voltages. This decrease relates to the increase of the electron density near the reverse faces of the both electrodes.

The electron temperature inside the electrodes increased from 5 to 7 eV near the electrodes when the applied VHF voltage was increased from 80 to 150 V for the constant gas pressure of 133 Pa. The decrease of the electron temperature in the center between the electrodes with increasing the applied voltages was less than 0.4 eV. The increase of the electron temperature near the reverse side of the electrodes was small compared to that inside the electrodes.

We found that the overloaded VHF voltages influence the expansion of the discharge area outside the electrodes through the escape of the power which is not absorbed inside the electrodes. In addition, the electron temperature near the electrodes increased with increasing the applied voltages. From these results, the overload of the VHF voltages, that is, the oversupply of the power causes the degradation of the film quality.

4. Conclusion

In this paper, we examined the dependences of a hydrogen plasma produced by the balanced power feeding method on the gas pressure and the applied VHF voltage by using the Plasma Hybrid Module of the software PEGASUS. The electron density outside the electrodes decreased drastically when the gas pressure is higher than 200 Pa. On the other hand, inside the electrodes, the electron density peaked at 400 Pa, and the power absorption increased and the electron temperature decreased with increasing the gas pressure. For the low applied VHF voltages, the electron density inside the electrodes was a decade higher than that outside the electrodes. However, the electron density outside the electrodes rose with increasing the applied voltages and overcame that inside the electrodes at 150 V. The power was more absorbed inside the electrodes for larger applied voltages, however, the absorption efficiency was reduced by increasing the applied voltages. It is concluded that the balanced power feeding method is suitable for producing VHF plasma at high pressures and at low applied voltages, leading to the fabrication of the microcrystalline silicon solar cell with qualified film deposition.

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