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Investigation of VHF Argon Plasma at High Pressure by Balanced Power Feeding Using Laser Thomson Scattering

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The dependences of the VHF plasma parameters on the gas pressure and power were examined by using the Laser Thomson scattering method, where the VHF plasma was produced in the high pressure region by the balanced power feeding method. It was found that the balanced power feeding method provides a high electron density plasma with low electron temperature at high pressures. This characteristics were confirmed by calculations using a 2-dimensional simulation code.

Key words: *VHF plasma, laser Thomson scattering, balanced power feeding, 2-dimensional simulation*

1. Introduction

A very high frequency (VHF) plasma is widely used for the fabrication of microcrystalline silicon thin film solar cells[1,2] because it provides high deposition rates. Recently the high pressure depletion method[3,4] has been proposed to increase the deposition rate. In this case, the VHF plasma is produced with the narrow discharge gap at high pressures. Now faster depositions of microcrystalline silicon are needed for further cost reduction of solar cells. The deposition rate is proportional to the electron density, so that the production of a higher electron density plasma is required from industry.

A VHF plasma is characterized by electron trapping, that is, the electron displacement δ_x should be shorter than a spacing gap between discharge electrodes for $\omega \ll \upsilon_m$[5]:

$$\delta_x = qE_0/(m_e \omega \upsilon_m) \ll d/2 \qquad (1)$$

Here d is a spacing gap between discharge electrodes, ω and υ_m is the angular frequency of VHF power source and electron collision frequency, respectively, and q, m_e and E_0 is electron charge, electron mass and the amplitude of the VHF electric field. Electron trapping effect provides better confinement of electrons and as a result the electron density becomes high. Eq. (1) indicates that E_0 and υ_m are important parameters in the VHF plasma, that is, the VHF power and pressure are key parameters in the VHF plasma characteristics. When VHF powers are increased, the amplitude of the VHF electric field E_0 increases and as a result the condition for electron trapping, $\delta_x \ll d/2$, is not valid. Therefore, to increase υ_m by increasing the pressure is required for VHF plasma discharge at high powers. Thus, it is an important subject in the production of microcrystalline silicon solar cells to examine the characteristics of the VHF plasma produced with a short gap discharge.

The Langmuir probe method is mostly used to investigate the characteristics of the VHF plasma such as the electron density (n_e) and the electron temperature (T_e). However, the plasma parameters with the narrow gap discharge will be seriously disturbed when the probe is inserted. In addition, the probe cannot be used at high pressure because the ion mean free path is much shorter than the sheath length, leading to the overestimation of the ion density[6].

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In the previous paper[7], we examined how the photo-ionization of metastable argon atoms affects the Thomson scattering spectrum and at which laser power density the photo-ionization becomes a problem for the laser Thomson scattering (LTS) diagnostics of argon plasmas. We succeeded in removing the influence of the photo-ionization of the metastable argon atoms on the Thomson scattering spectrum from the VHF argon plasma by reducing the power density of the YAG laser below 1×10^{13} W/m^2. Thus, we consider that the LTS can be a powerful diagnostic method under such conditions.

In this paper, we examined the dependence of the VHF plasma parameters on the pressure and power by using the LTS method, where a VHF plasma was produced by a balanced power feeding method[8] in addition to the conventional power feeding method. In addition, we tried to simulate the VHF plasma using the Plasma Hybrid Module (PHM) of PEGASUS software.

2. Experimental Setup

Figure 1 shows the schematic diagram of the LTS system on the VHF plasma. The chamber (diameter 200 mm, length 400 mm) was designed specifically for the LTS measurements. The chamber was equipped with baffles, two Brewster windows, a beam dump and a triple grating spectrometer (TGS). The structure and the function of TGS have been reported in Ref. 8). This TGS made us possible to detect the Thomson scattering spectrum at 1nm away from the laser wavelength without the problem of the stray light. Finally, the scattered light signals passed through the TGS were detected by an ICCD camera (Princeton Instruments, PI-MAX Ⅲ). The quantum efficiency of the camera was ~50 % at $\lambda = 532$ nm. The photon counting method was used to enable reliable measurements of small scattered signals.

The VHF plasma of 60 MHz was sustained between two parallel plate electrodes (60 mm × 60 mm × 8 mm) made of stainless steel and the distance between two electrodes was always kept at 10 mm. The working gas was argon, the gas pressure used in this study was ranged from 100 mTorr to 1000 mTorr and the VHF power was in the range between 20 W to 80 W. In the case of the conventional power feeding method, one electrode was connected to the power supply through the matching box and another electrode was connected to the ground. This kind of power feeding system has been commonly applied for many studies on plasma processes. However, abnormal discharges may happen between the power feeding cable and the chamber wall in the VHF range. In order to avoid such abnormal discharges, we used a balanced power feeding method[9]. Then the plasma was mainly produced in the region between the two electrodes.

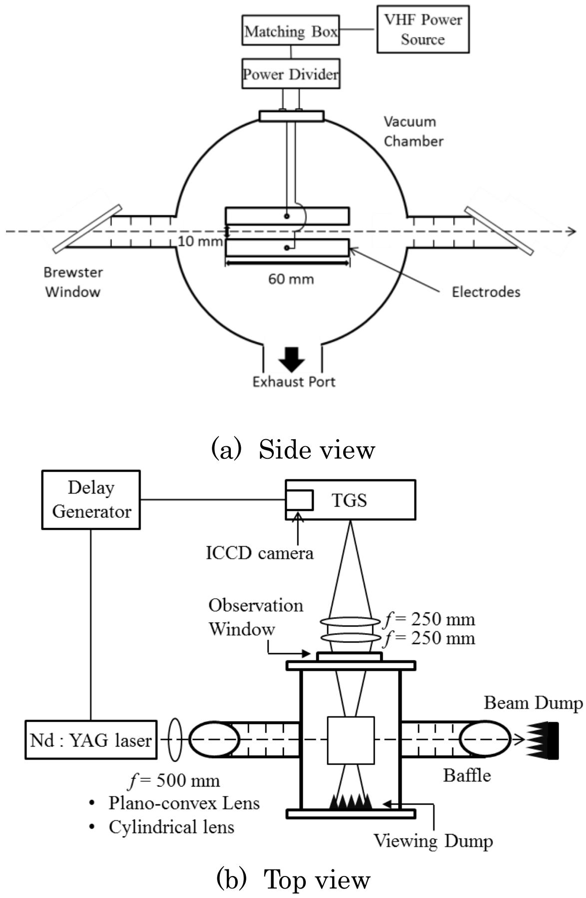
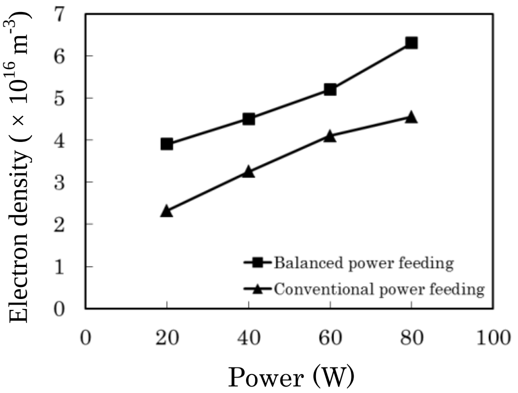


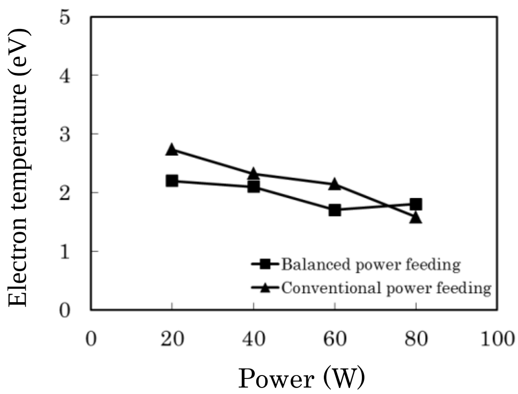
Fig. 1 Schematic diagram of the experimental setup.

3. Results and Discussion

In order to examine the effect of the conventional power feeding and balanced power feeding method on the plasma parameters, we measured n_e and T_e using the LTS system as a function of VHF power. As seen in Fig. 2, when the VHF power is increased from 20 watt to 80 watt, n_e increases from 3.9×10^{16} m^{-3} to 6.3×10^{16} m^{-3} for the case of balanced power feeding method. n_e values obtained for the case of the balanced power feeding method were higher about 40 % than those obtained for the conventional power feeding method. Thus, we conclude that the balanced power feeding method provides higher electron density. On the other hand, as seen in Fig.2 (b), T_e decreases with increasing the power independent of the power feeding method.



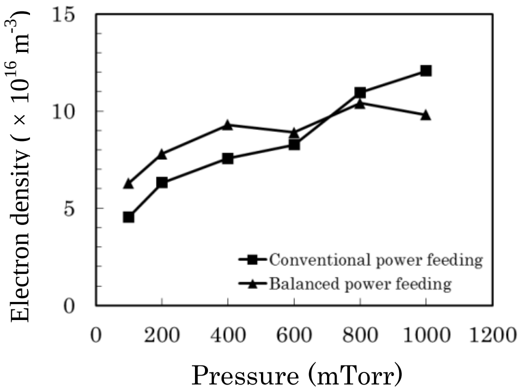
(a)



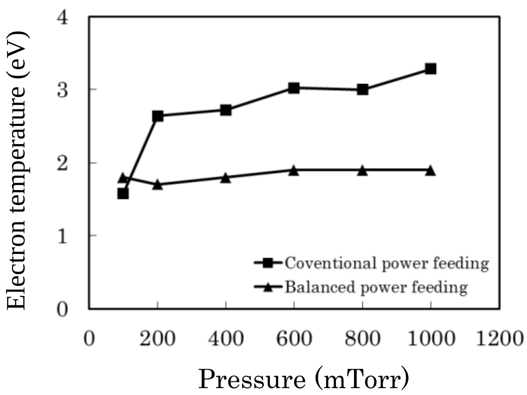
(b)

Fig. 2 Dependences of the electron density (a) and the electron temperature (b) on the VHF power are compared for the case of the balanced power feeding method and the case of the conventional feeding method. Here the pressure was 100 mTorr.

Then we measured the dependence of the plasma parameters on the gas pressure. Figure 3 (a) shows that when the pressure is increased, the electron density increases. This is understood by electron trapping effect described in Sec. 1. Looking at carefully Fig. 3 (a), the results can be divided into two parts in the case of using the balanced power feeding method. In the first part, n_e increases from 6.3 × 10^{16} m^{-3} to 1.0 × 10^{17} m^{-3} when the gas pressure is increased from 100 mTorr to 800 mTorr. In the second part, when the gas pressure is increased from 800 mTorr to 1000 mTorr, n_e decreases slightly from 1.0 × 10^{17} m^{-3} to 9.8 × 10^{16} m^{-3}. On the other hand, n_e increases from 4.6 × 10^{16} m^{-3} to 1.2 × 10^{17} m^{-3} when the conventional power feeding method is used. The average n_e ratio of the balanced power feeding method is 20 % lower than that by conventional power feeding method when the gas pressure is higher than 800 mTorr. This may be explained by the fact that the VHF discharge tends to be localized when the pressure is increased and, as a result, the plasma region moves to the electrode side. Figure 3 (b) shows that T_e is always kept around 1.8 eV independent of the pressure when the balanced power feeing method is used. In the case of the conventional power feeding method, T_e is around 3.0 eV except at 100 mTorr. Note that the balanced power feeding method provides lower electron temperature plasma that is favorable for plasma processes.



(a)



(b)

Fig. 3 Dependences of the electron density (a) and the electron temperature (b) on the gas pressure are compared for the case of the balanced power feeding method and the case of the conventional feeding method. Here the VHF power was fixed at 80 W.

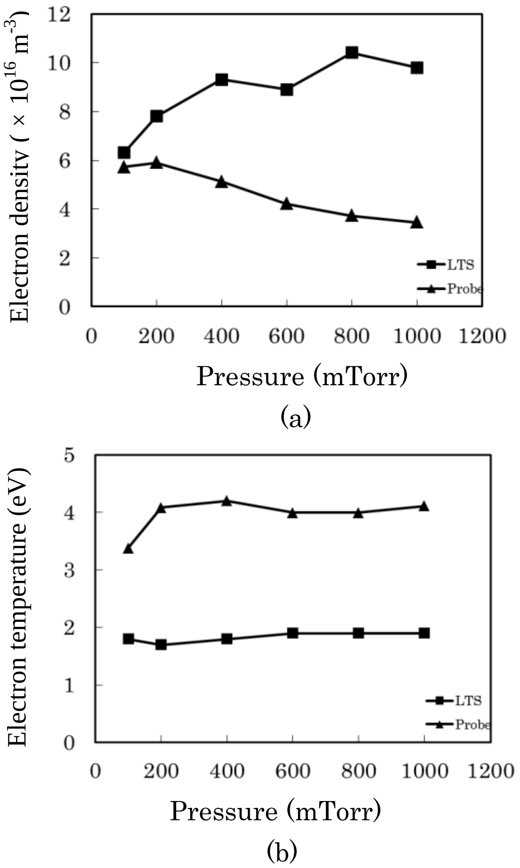


Fig. 4 Electron densities (a) and electron temperatures (b) measured by the LTS method and Langmuir probe method for different gas pressures. Here the VHF power was fixed at 80 W.

Nishimiya[9)] suggested the advantage of the balanced power feeding method, where the Langmuir probe was used as a diagnostic tool. In our previous study[7)], we examined the dependence of n_e and T_e by the LTS and Langmuir probe on the VHF power at the pressure of 100 mTorr. Recently there is a tendency operated at higher pressure in plasma processes to get higher deposition rates. In this paper, we investigated the characteristic of LTS method and Langmuir probe method at the gas pressrue higher than 100 mTorr. As seen in Fig. 4, when the gas pressure is 100 mTorr, n_e values measured by the LTS method and Langmuir probe method are 6.3 × 10^{16} m^{-3} and 5.7 × 10^{16} m^{-3}, respectively. The T_e value measured by LTS method is lower than that by probe method. This tendency agrees with the result reported in Refs. 10) and 11). When the gas pressure is increased to 1000 mTorr, n_e measured by LTS method increased. On the contrary, n_e measured by the probe method decreases. This different tendency may due to the fact that the probe cannot be used at the higher gas pressure, as described in Sec. 1. Thus, we conclude that the LTS is a reliable diagnostic method at high gas pressures.

We have performed the simulation of a VHF plasma by using the Plasma Hybrid Module (PHM) of PEGASUS software Inc.[12,13)]. The detail of the PHM was described in Ref. 14). Figure 5 shows the Balanced Power Feeding (BPF) model which uses a cylindrical coordinate system with axial symmetry. Here, we briefly schematic 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 the Monte Carlo method, are calculated by the fluid model and the equation of the electron motion. A pair of parallel plate electrode with the radius of 34 mm was set at the center of a cylindrical chamber. The gap between the electrodes was fixed to 8 mm. The working gas was argon, the gas pressure used in this simulation was 100 mTorr and the amplitude of the applied voltages was in the range between 60 and 100 V. The argon gas was introduced from the centered top position of the chamber. An exhaust port was located on the bottom face of the chamber. In order to suppress the plasma emission from the outside surfaces of the electrodes, we covered it with insulators. However, the leak currents of the electrode are not considered in the model, thus, the effect of the applied VHF voltages in the BPF model on the VHF plasma with short-gap parallel electrodes was investigated.

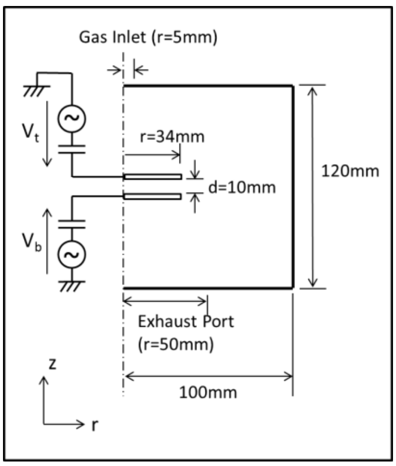


Fig. 5 Schematic diagram of BPF model.

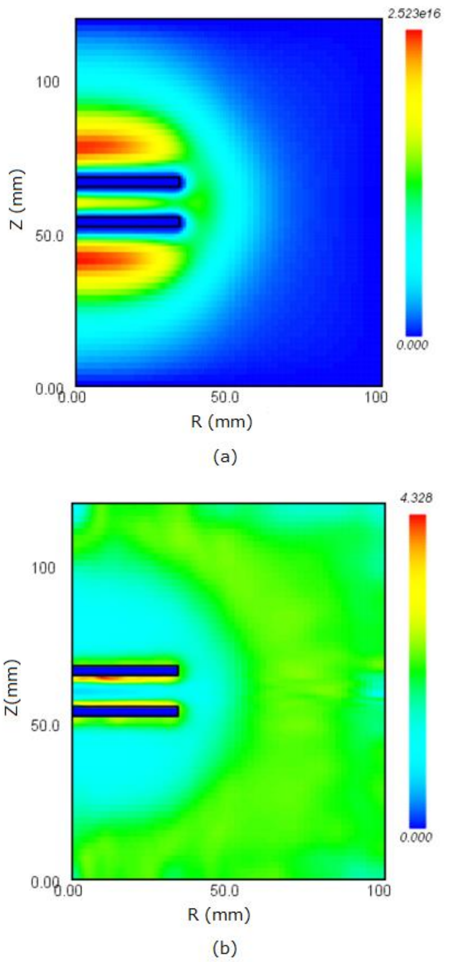


Fig. 6 Spatial distributions of the electron density (a) and the electron temperature (b) at the gas pressure of 100 mTorr. The images are 2-D in the balanced power feeding model (V_{rf} = 60 V).

Figure 6 shows the 2-dimensional images of the electron density and the electron temperature in the BPF model. Here the frequency of the VHF power source and the amplitude of the VHF voltage are 60 MHz and 60 V, respectively. The gas pressure was set to 100 mTorr. The n_e and T_e values at the center of the electrodes in the BPF model are 1.5 × 10^{16} m^{-3} and 1 eV, respectively.

Figure 7 demonstrates the applied voltage dependence of the n_e and T_e distributions. The distributions are in the z direction and are calculated at the radial position r = 20 mm. Obviously the highest n_e appears at the center position between two electrodes. The central n_e values for the applied voltage of 60 V, 80 V and 100 V are 1.5 × 10^{16} m^{-3}, 2.6 × 10^{16} m^{-3} and 4.1 × 10^{16} m^{-3}, respectively. In addition, T_e is kept around 1 eV at the center independent of the applied voltage. Besides, Fig. 7 shows that the plasma is produced outside the discharge electrode and the n_e distribution outside the electrode takes a peak at z = 18 mm, namely 8 mm apart from the power electrode, and then, n_e decreases with the distance from the electrode. The VHF power of 20 W, 40 W, 60 W and 80 W in our experiment correspond to the V_{rf} of 28 V, 37 V, 45 V and 50 V, respectively. Therefore, we compared the measure plasma parameters obtained for the VHF power of 80 W with the calculated parameters by the simulation setting the applied voltage of 60 V. The n_e values obtained by the LTS method and the simulation model are 6.2 × 10^{16} m^{-3} and 1.5 × 10^{16} m^{-3}. On the other hand, the T_e value obtained by the simulation model is 1 eV, and it is slightly lower than that by the LTS method. In any case, these results indicate that the plasma parameters obtained by the simulation are not so much different from those measured by the LTS method.

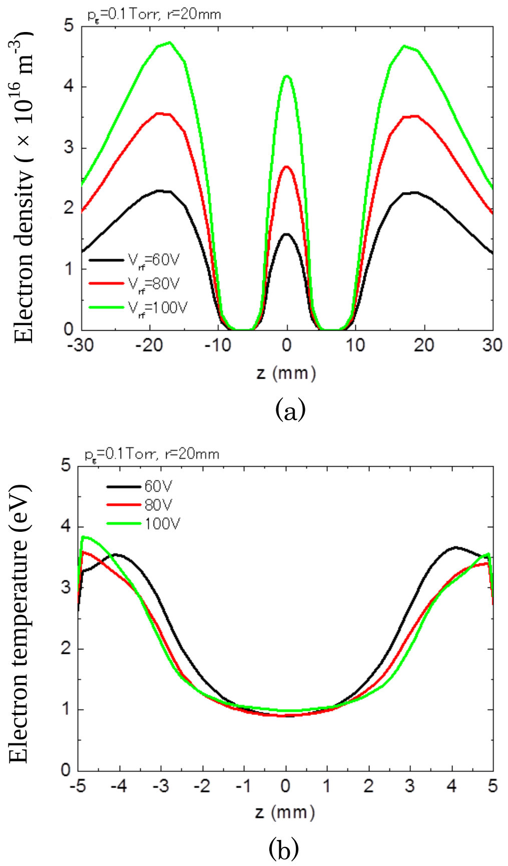


Fig. 7 Spatial distributions of the electron density (a) and the electron temperature (b) for different applied voltages. The gas pressure was 100 mTorr, the distance of the electrodes was d = 8 mm. The distributions are in the z direction and are calculated at the radial position r = 20 mm.

4. Conclusions

We examined the dependence of the VHF plasma parameters on the gas pressure and the VHF power by using the LTS method. Here the VHF plasmas were generated by the balanced power feeding method and conventional power feeding method. Compared with the conventional power feeding method, n_e and T_e by the balanced power feeding method showed the outstanding performance not only on the dependence of the pressure but also on the power. In addition, we measured the pressure dependence of the plasma parameters by the LTS method and the Langmuir probe method at high pressure that was reported as an indispensable condition for VHF plasma processes. It was found that as the gas pressure is increased from 100-1000 mTorr, the n_e values measured by the Langmuir probe method showed the different tendency from the values measured by the LTS method. This is considered that the Langmuir probe method is not reliable for high pressures at around 1 Torr.

We have successfully simulated the VHF argon plasma using the PHM of PEGASUS software. The 2-D spatial distributions of n_e and T_e indicate that the plasma is produced outside the discharge electrode in the balanced power feeding model. The n_e and T_e values inside the electrodes in the BPF model are 1.5×10^{16} m^{-3} and 1 eV, and these values are not so much different from those measured by the LTS method. Therefore, it is concluded that both LTS diagnostics and the simulation can be powerful tools to study VHF plasmas.

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