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Properties of Inductively Coupled Hydrogen Plasmas Sustained with Multiple Low-Inductance Internal-Antenna Units

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For large-area processing required in fabrications of flat panel displays and microelectronic devices, cylindrical inductively-coupled plasma (ICP) sources have been developed with multiple low-inductance antenna (LIA) units. Cylindrical RF plasma sources with four LIA units exhibited stable source operation even at 2000 W RF powers to attain plasma densities as high as 8×10^9 cm^{-3} at hydrogen pressure of 1.3 Pa. In these plasmas, effective suppression of electrostatic coupling has been simultaneously achieved mainly due to low-voltage operation of ICPs. Hydrogen atom density measured using vacuum ultraviolet absorption spectroscopy was as high as 10^{11} cm^{-3}.

Key words: Plasma, Hydrogen, ICP, Internal-antenna, Large area plasma source

1. INTRODUCTION

Development of large-area plasma sources with high plasma density is desired for fabrication of microelectronics devises and flat panel display (FPD), which are tended toward substrate enlargement and high throughput mainly due to cost reduction of the fabrication processes.

Among various high-density plasma sources such as capacitively-coupled plasma (CCP) [1], inductively-coupled plasma (ICP) [2-5], electron cyclotron resonance (ECR) plasma [6-9], and surface wave plasma (SWP) [10], ICPs attract great interests as one of the promising candidates of large-area high-density plasma source.

In scaling up of ICP sources with conventional antenna configuration such as a spiral antenna placed on top of a reactor, the antenna size and hence the antenna impedance is tended to become larger for large-area plasma generation. However, the increase in the antenna size and/or the impedance raises problems associated with anomalous rise of antenna terminal voltages and formation of standing wave, which result in non-uniform RF current distribution and hence non-uniform plasma profile [11].

In order to solve these problems, we developed ICP sources with multiple low-inductance antenna (LIA) units. For plasma processing of large-area substrates such as 300 mm wafers, cylindrical plasma source of 500 mm in diameter with multiple LIA units have been developed. Previous experiments with multiple LIA units resulted in stable source operation even at 3000 W RF powers to attain plasma densities as high as 10^{11} - 10^{12} cm^{-3} and floating potentials as low as 4 - 6 V in argon [12].

In plasma processes including chemical vapor deposition (CVD), etching and ashing, it is important to control radical density together with plasma density and plasma potential. Especially hydrogen (H) atoms are widely recognized to play important roles in deposition of carbon and silicon related films [13,14].

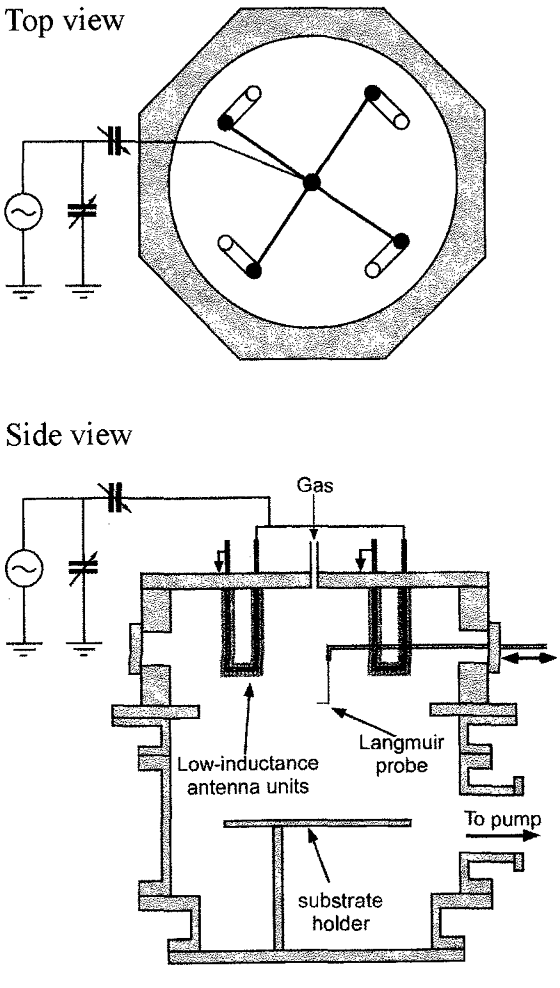

Fig. 1. Schematic diagram of reactor.

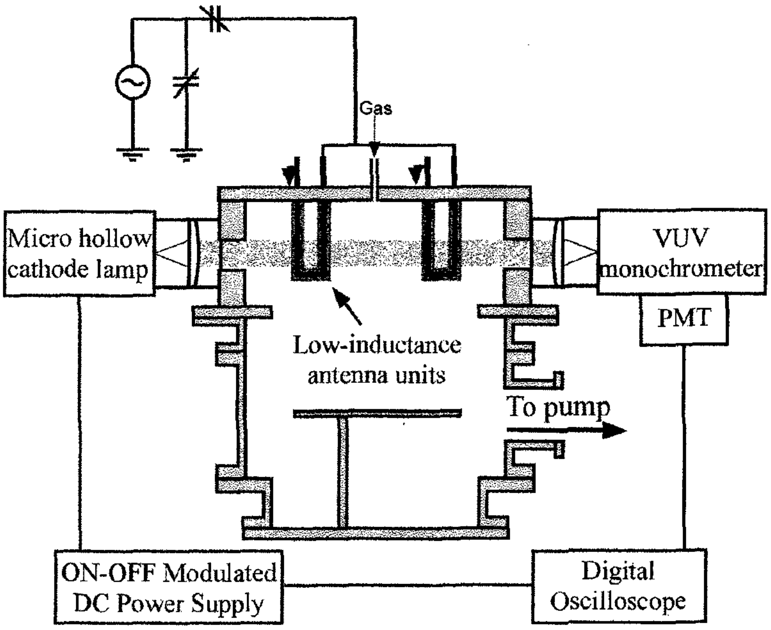

Fig. 2. Schematic diagram of VUVAS system.

In this paper, properties of hydrogen plasmas sustained with this cylindrical plasma source are reported in terms of plasma density, radical density and plasma potential.

2. EXPERIMENTAL

The schematic diagram of the chamber with a set of the LIA units is shown in Fig. 1. The LIA unit consists of a U-shaped antenna conductors with a 50 mm width and a 160 mm height, which is fully covered with dielectric tubing for complete isolation from the plasma [12]. Four LIA units are mounted on the top flange of the discharge chamber and are coupled to 2000 W RF power generator at 13.56 MHz via a matching network. Each LIA unit was connected in parallel to the matching network. This chamber had a 500 mm inner diameter and a 200 mm height, which was connected to a diffusion part of the chamber made of stainless-steel vessel with a 500 mm inner diameter and a 400 mm height. H_2 gas was supplied at a flow rate of 30 sccm from the top flange and a total pressure was maintained in a range of 1.3 - 3.9 Pa.

Figure 2 shows a schematic diagram of a vacuum ultraviolet absorption spectroscopy (VUVAS) system, which was additionally installed to the discharge chamber. Density of atomic hydrogen in discharges was measured with the VUVAS system using a microdischarge hollow-cathode lamp (MHCL) as the light source of the vacuum ultraviolet light of Lyman α (L_α) line (121.6nm) [15]. The VUV light from the MHCL passing through the discharge region was detected using a vacuum ultraviolet monochromator equipped with a photomultiplier tube (PMT). The PMT outputs were measured to evaluate VUV light absorption by H atoms, whose density in the plasma can be measured from the absorption.

Plasma parameters were measured with a cylindrical Langmuir probe radially inserted at 200 mm beneath the top flange. The antenna terminal voltages were measured at the high-voltage end of the antenna conductor.

3. RESULTS AND DISCUSSION

Figure 3 shows dependence of plasma density on input RF power P_{rf} for hydrogen plasmas sustained at a pressure of 1.3 Pa. The plasma density slightly increases from 2.7×10^8 cm^{-3} at P_{rf} = 100 W to 1.0×10^9 cm^{-3} at P_{rf} = 800 W and then drastically increases to 8.2×10^9 cm^{-3} at P_{rf} = 2000 W. The drastic increase of the plasma density in the region over $P_{rf} >$ 1000 W is considered to occur due to transition from the capacitive discharge mode known as E discharge to the inductive discharge mode known as the H discharge [16].

Figure 4 shows dependence of antenna terminal voltage amplitudes on input RF power P_{rf} for hydrogen plasmas sustained at a pressure of 1.3 Pa. The amplitude of antenna terminal voltage for hydrogen plasma is measured to be less than 720 V. The values were markedly smaller than those for argon plasma obtained with the hemispherical multi-turn antenna (~ 4000 V) [17] and the double half-loop antenna (~ 1000 V) [18]. The lowering of the antenna terminal voltage is expected to provide a significant effect on suppression of the potential in the plasma, since the antenna terminal voltage is considered to be the source term of the electrostatic coupling. In the case of the antenna which is completely covered with an insulator, the electrostatic voltage to the plasma is applied as a portion of the antenna voltage used up in the sheath region after subtracting the voltage drop through the insulator. Therefore, the reduction in the antenna voltage is considered to be significant for suppression of the electrostatic coupling, which may lead to suppression of potential in the plasma.

The floating potential measured for hydrogen plasmas sustained at a pressure of 1.3 Pa is shown in Fig. 5 as a

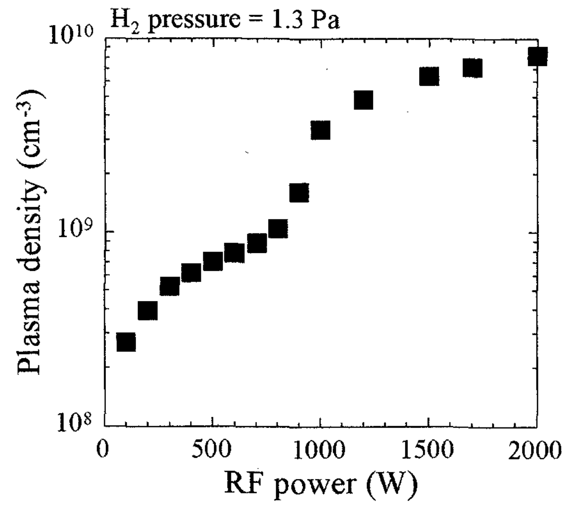

Fig. 3. RF power dependence of plasma density for hydrogen plasmas.

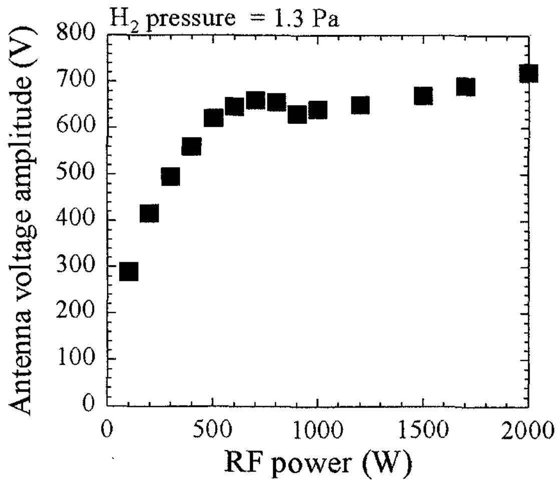

Fig. 4. RF power dependence of antenna terminal voltage for hydrogen plasmas.

measure of evaluating the electrostatic coupling. Temporally averaged values of the floating potential (DC component) were 7.9 - 8.4 V in the range of $P_{rf} \leq 800$ W and drastically decreases to 6.0 V at $P_{rf} = 1000$ W and then is almost constant in the range of $P_{rf} = 1000 - 2000$ W. Recalling that the electrostatic coupling to the plasma is considered to be applied as a portion of the antenna voltage used up in the sheath region after subtracting the potential drop through the insulator surrounding the antenna conductor, the reduction of the potential in the plasma with increasing RF power is considered to be attributed to the lowering of the impedance in the sheath region due to the sheath shrinkage with increasing plasma density as shown in Fig. 3.

These results demonstrate that the plasma generation regime using LIA units allows low-voltage operation of ICP, which is especially significant in CVD process to synthesize high-quality films with markedly reduced plasma damage.

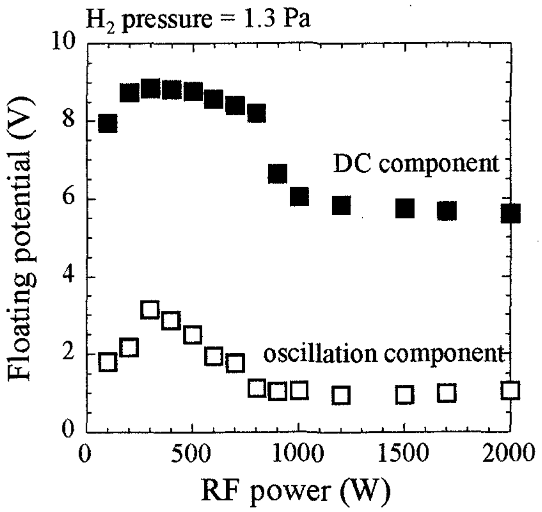

Fig. 5. RF power dependence of floating potential for hydrogen plasmas.

Figure 6 shows power dependence of absorption intensity of L_α line (121.6 nm). The absorption intensity of L_α in hydrogen plasma increased from 46 % to 83 % with increasing P_{rf} from 100 W to 1500 W. H atom density estimated from these results is as high as 10^{11} cm^{-3} in the range of $P_{rf} \leq 500$ W. In the region of $P_{rf} \geq 500$ W, however, the absorption intensity of L_α line is in saturation region, in which the H atom density is considerably higher than 10^{11} cm^{-3}.

The saturation of the absorption is considered to be caused by the absorption path length of the VUV light in the present study. Further experiments are underway with an experimental setup employing a shortened path length.

4. CONCLUSIONS

Properties of hydrogen plasmas sustained with four LIA units are reported for the cylindrical plasma source of 500 mm in diameter. Conclusions obtained in this study are summarized as follows.

1) Experiments with four LIA units resulted in stable source operation up to 2000 W RF powers to attain plasma densities as high as 10^9 cm^{-3} at a hydrogen pressure of 1.3Pa.

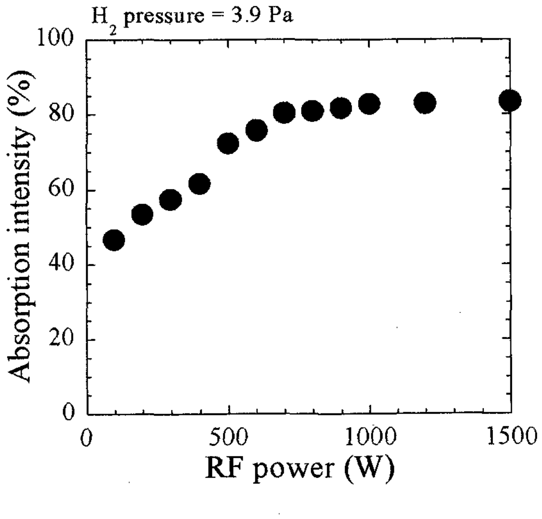

Fig. 6. RF power dependence of absorption intensity for L_α.

2) The amplitude of the antenna RF voltage is less than 720 V and floating potentials were as low as 6 - 7 V. These results demonstrate that the plasma generation using LIA units allows low- voltage operation of ICP.
3) Hydrogen atom density estimated in the range of $P_{rf} \leq 500$ W was as high as 10^{11} cm^{-3}.

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