High-density microwave plasma spots produced by multi-hollow window technique

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High-density uniform microwave plasmas are conventionally produced by exciting surface waves along a flat dielectric window. In this paper, a novel method called multi-hollow window (MHW) technique is presented, which was developed for microwave plasma control at high pressures (1 ~ 50 Torr). In this MHW technique, many hollows of 5-15 mm in diameter are regularly distributed in a dielectric window surface. When the microwave discharge is turned on at high pressures, high-density plasma spots are generated inside each hollow as easily recognized in the plasma optical emission image. Mechanism of plasma spot generation is different from so-called hollow cathode discharge but interpreted by transit time heating of electrons at plasma resonance layer.

1. Introduction

There has been a great need for meter-scale high-density plasma sources for manufacturing giant microelectronics devices such as liquid crystal display and solar cell. Large-area capacitively coupled plasmas (CCPs) have widely been used for large-scale CVD and etching processes. However, the 13.56 MHz CCPs have drawbacks of low plasma densities ($<10^{10}$ cm^{-3}). Latest studies in a range of VHF (30 – 100 MHz) revealed considerable increase in plasma density, however standing wave effect and edge effect significantly degrade the plasma uniformity.

On the other hand, we have recently succeeded in producing a high-density (10^{11}-10^{12} cm^{-3}) plasma of 2 m in length and 0.5 m in width by microwave discharge at 915 MHz [1]. Such high-density large plasma has never been produced by capacitively coupled RF discharges. The key technologies developed in this microwave discharge are a vacuum waveguide and a carefully-designed slot antenna array for excitation of surface waves in meter-scale.

This surface wave plasma source enabled high speed (~3 nm/s) deposition of micro-crystalline silicon thin films of 2 m long 0.3 m wide large area for solar cell applications [1]. However, the defect density of deposited film is higher than the acceptable levels, which may be caused by excess dissociation of mono-silane gas (SiH_4) at relatively low pressures (~0.1 Torr). In order to improve film qualities, higher pressure operation is preferable where plasma moderately dissociates source gas with lower electron temperatures. At high pressures, however, plasma tends to localize around the multi-slot antenna. To overcome this issue, we developed a novel technique for microwave discharge, that is, *multi-hollow window* (MHW) technique.

2. Experimental

2.1. Multi-hollow window

Fig. 1(a) shows the side view of the experimental apparatus. One slot antenna (10 x 165 mm in size) is arranged on the bottom of the waveguide, looking upon perpendicular to the microwave injection direction. One flat quartz plate (243 x 243 x 35 mm in size) is placed between the slot and the rectangular parallelepiped chamber (430 x 430 x 315 mm in size). We prepared three quartz plates of 5 mm in thickness which had a series of multi-hollow of diameters (5, 10 and 15 mm). Fig. 1(b) schematically shows a part of multi-hollow regularly distributed in a quartz window. Measurements were performed by alternately locating each of these plates underneath the flat plate.

Spatial distributions of plasma parameters and Ar optical emission intensity were measured by moving a spherical probe (made of gold, 1 mmϕ) and an optical fiber (0.4 mmϕ). Argon microwave plasma was produced by 915 MHz microwave power incident through the slot and the quartz plate. The gas pressure was ranged from 0.01 to 10 Torr while the microwave power was changed from 100 to 1000 W.

2.2. Optical emission intensity measurements

For example, as shown in Fig. 1(c), when plasma is generated by using this multi-hollow window, strong luminosity is observed within each hole of 10 mm in diameter and 20 mm in interval for the net microwave power of 500 W and argon pressure of ~7.5 Torr. Thus it implies that plasma of extremely high density is locally produced inside the hollows. Such widely-spread high-density plasma spots make the global plasma distribution more uniform than the flat window case.

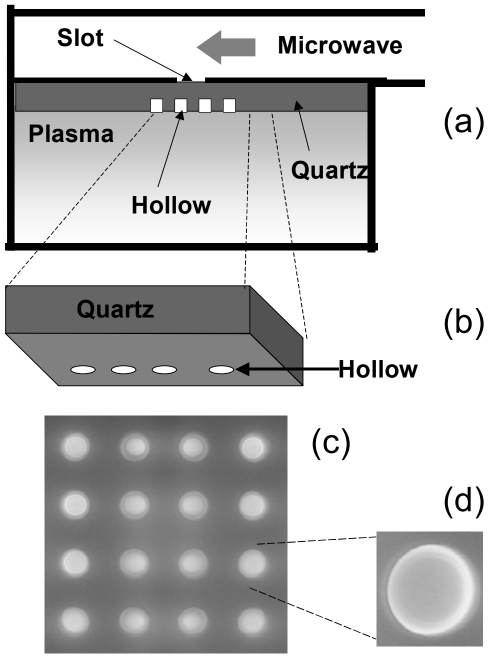

Fig. 1 (a) The side view of experimental apparatus,
(b) multi-hollow prepared in quartz window,
(c) optical emission image of plasma,
(d) optical emission image of single hollow at high pressure.

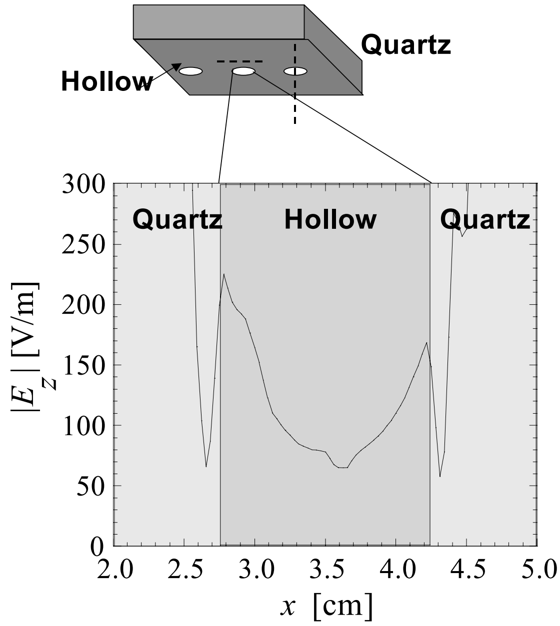

Fig. 2. Microwave field distribution across a hollow containing uniform plasma, simulated by FDTD method.

When the pressure is 0.1 Torr or lower, the luminosity is almost uniform inside the hollow with slightly brighter at the central part. At pressures higher than 0.5 Torr, however, ring-like bright region appears along the inner wall of the hollow. Fig. 1(d) displays such example at 1 Torr where the central region is dark compared with the periphery inside the hollow. It should be noted that, with increasing pressures, the plasma is condensed into each hollow while the plasma diffused from hollows are significantly suppressed due to small diffusion rate at higher pressures.

Another MHW effect is suppression of plasma density jump and standing surface wave modes which are usually observed in case of flat dielectric window. This can be understood as a result of scattering of surface waves at the high-density plasma spots existing at the pitch comparable to or shorter than the wavelength.

3. Mechanism of plasma spot generation in MHW

It is well known in high-pressure DC discharge that high-density plasma is produced within a hollow cathode due to a good confinement of ion-induced secondary electrons in a potential well of the hollow cathode. In the present case, ion bombarding energy is too low (~20 eV) to emit secondary electrons. Thus, electrons are considered to be accelerated directly by intense microwave fields near the hollow inner wall.

To understand the interaction between electrons and microwave fields, three-dimensional analysis of the fields were made using a finite difference time domain (FDTD) simulation code. Fig. 2 shows the simulation result of electric field distribution around a hollow where a constant electron density was assumed with the same geometry as in the experiment. The field intensity is maximum at the wall and decreases inside the plasma.

The real experiment, however, the plasma density is non-uniform and there exists a plasma resonance layer where an extremely strong local field appears, resulting in transit-time heating of electrons. Calculation in a simplified model suggests that electrons get a large energy (~several eV) in a single transit if the fields are enhanced at the resonant layer. More details are presented in the conference.

4. References

[1] H. Sugai, Y. Nojiri, Y. Hotta, T. Ishijima, H. Toyoda, A. Masuda, M. Kondo, Abstracts of 2007 Material Research Society Spring Meeting (San Francisco, 2007) 5.