

# Advanced Plasma Technology

*Edited by*

*Riccardo d'Agostino, Pietro Favia, Yoshinobu Kawai,  
Hideo Ikegami, Noriyoshi Sato, and  
Farzaneh Arefi-Khonsari*



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## Preface

Plasma processes started to be applied for surface modification of materials in the 70's, in the fields of microelectronics (dry etching processes for fabricating integrated circuits) and semiconductors (deposition processes of semiconductor thin films for solar cells). Since then, enormous advancements in the basic, diagnostic and experimental aspects of plasma sciences have been made, so that many other science areas and industrial fields have been permeated by plasma processes: polymers, textiles, biomaterials, microfluidics, composite materials, paper, packaging, automobile, waste treatment, cultural heritage and corrosion protection, to mention but a few.

The idea of organizing this book was developed during the second International School of Industrial Plasma Application, held at Villa Monastero in Varenna, Italy, in October 2004, where approximately one hundred attendees from all over the world were assembled. The aim of the School was to describe, in a tutorial way, the numerous modern industrial applications of plasmas.

Now, three years later, this book is issued with the same tutorial purpose: to describe advances of low and atmospheric pressure plasmas in technological fields, such as polymers, semiconductors, solar cells, biomaterials, displays, water treatment, and space, with the introduction of some fundamental chapters on diagnostics, reactor design, modeling and process control.

Advanced Plasma Technology is a collection of 25 chapters on various aspects of plasma processes authored by well known plasma scientists. We are convinced that this book will be of help to both students and researchers, in academia as well as in the industry.

To all the authors, to the referees and to our publishers at Wiley-VCH we would like to extend our warmest "thank you" for the creation of this book. We hope that you, reader, will enjoy reading this book as much as we enjoyed editing it.

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## 1

**Basic Approaches to Plasma Production and Control***N. Sato*

Plasma production and control are of crucial importance for “intelligent” plasma processing in next-stage material and device manufacturing. The author has been concerned with basic experiments on discharge plasmas along this line of research. Here are presented some essential points of basic approaches to plasma production and control. They include works on large-diameter plasma production, electron-temperature and ion-energy controls, and dust particle collection and removal.

At first, two methods of plasma production are presented. They are for high-density electron cyclotron resonance (ECR) and rf plasmas yielding uniform plasma processing in actual manufacturing devices, the diameters of which are larger than several tens of centimeters. These discharge plasmas are produced under low gas pressures. New approaches to medium-pressure and high (atmospheric)-pressure discharge plasmas are also described in some detail.

Electron temperature is continuously controlled in the wide range of one or two orders of magnitude in a region separated from a discharge region. The methods employed might be useful for finding the best conditions for various kinds of plasma processing. In fact, the methods have been proved to be useful for efficient production of negative ions, formation of high-quality diamond particles, and quality increase of a-Si:H film. A good method of ion-energy control should also be established for “intelligent” plasma applications. A new approach is presented for this purpose.

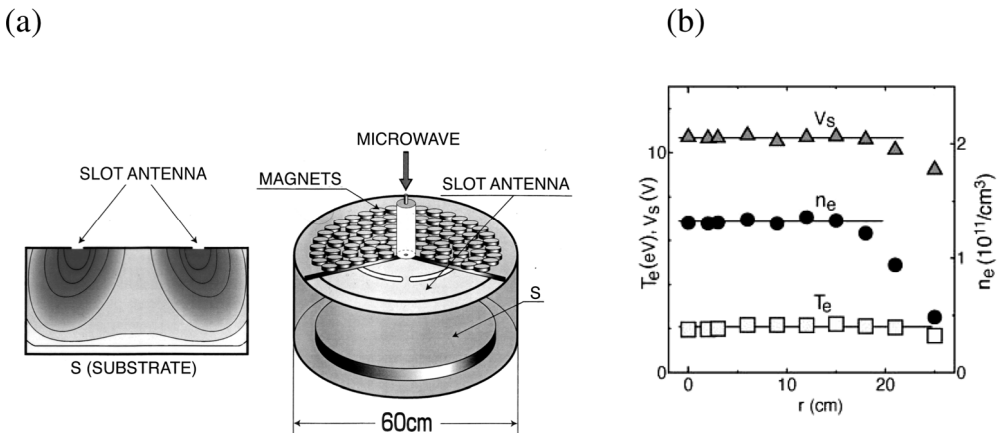
Dust collection and removal are quite important for many kinds of material and device manufacturing. On the basis of fundamental fine-particle behaviors in plasmas, we have proposed a simple method for collection and control of negatively charged fine particles in plasmas. Our collector is often called “NFP-Collector” (negatively charged fine-particle collector). The collector has been proved to be very efficient for collection and removal of dust particles levitating in plasmas, suggesting big effects on plasma processing.

## 1.1 Plasma Production

### 1.1.1 Under Low Gas Pressure (<0.1 torr)

Here, two simple methods are presented of plasma production for large-scaled uniform-plasma processing. One of the methods is based on ECR. For the other method, we employ the magnetron-type rf discharge. In both of them, weakly ionized plasmas are produced by low-pressure discharges in a vacuum chamber, the wall of which is separated into two parts. One part is electrically grounded and the other part is used as an antenna or rf electrode. Therefore, in principle, we need no additional electrode for plasma production in the vacuum chamber. Radial plasma profiles are non-uniform in a region of plasma production. But, radial plasma diffusion makes the plasmas uniform at an axial position a little away from the production region. We employ a magnetic field to provide efficient plasma production and to control plasma flow toward the wall (or electrode), which is closely connected with plasma loss and particle sputtering. The magnetic field, which is generated by permanent magnets, is used also to modify electron motions for plasma-profile control, although there is no direct magnetic effect on ions in front of substrates.

A schematic feature of ECR plasma production [1,2] is illustrated in Fig. 1.1(a). The antenna, which is situated at one end of a vacuum chamber, consists of a back plate with permanent magnets behind and a slotted plate separated from the back plate. A microwave of 2.45 GHz is fed through a coaxial waveguide to satisfy the ECR condition ( $\sim 875$  G) in a region near the magnet surfaces in front of the antenna. The slotted plate can be covered with a thin glass plate.



**Fig. 1.1** (a) Schematic of ECR plasma production using a plane-slotted antenna with magnets and (b) radial profiles of plasma parameters measured at  $z = 10$  cm.

The plasma produced is non-uniform radially in front of the antenna, depending on the positions of the slots and magnets. But, with an increase in  $z$  (distance from antenna front), inward plasma diffusion makes the plasma profile flat in the radial direction. Typical results are presented in Fig. 1.1(b), where argon pressure  $\approx 1.5 \times 10^{-2}$  torr and microwave power  $\approx 1$  kW. The plasma of density  $n_p \approx 1.3 \times 10^{11} \text{ cm}^{-3}$  is found to be uniform within 3% in the radial region of 35 cm in diameter at axial distance  $z$  of 10 cm. The plasma density is almost proportional to the microwave power. The axial position for the uniform radial plasma profile is controlled by changing the magnetic configuration in front of the antenna.

A reactive plasma produced by this method was confirmed to yield uniform etching of poly-silicon [3]. An antenna system shown in Fig. 1.2 has been proposed for actual plasma processing [4].

A schematic feature of modified magnetron-type (MMT) plasma production [5] is illustrated in Fig. 1.3(a). An rf power of 13.56 MHz is fed to a ring electrode of 55 cm in diameter and 7 cm in length, which is a central part of a cylindrical vacuum chamber of 55 cm in diameter. A discharge is triggered between this powered electrode and the other parts of the vacuum chamber, which are electrically grounded, in the range of argon pressure  $5.0 \times 10^{-4}$ – $5.0 \times 10^{-2}$  torr. Permanent magnets, which are situated just outside the cylinder to construct azimuthal magnet rings, provide magnetic mirrors axially near the inner surface of the ring electrode. This magnetic configuration enhances plasma production because high-energy electrons responsible for ionization move in the azimuthal direction, being well trapped in the magnetic mirrors inside the region near the ring electrode. This motion of electrons reduces a potential drop in front of the electrode, which is closely connected with an interaction of ions with the electrode.

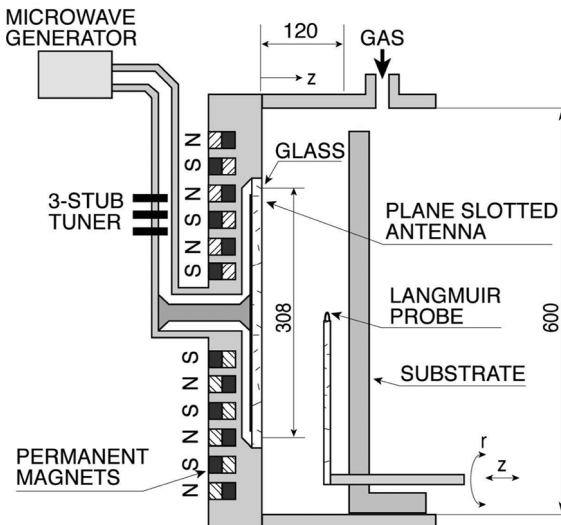
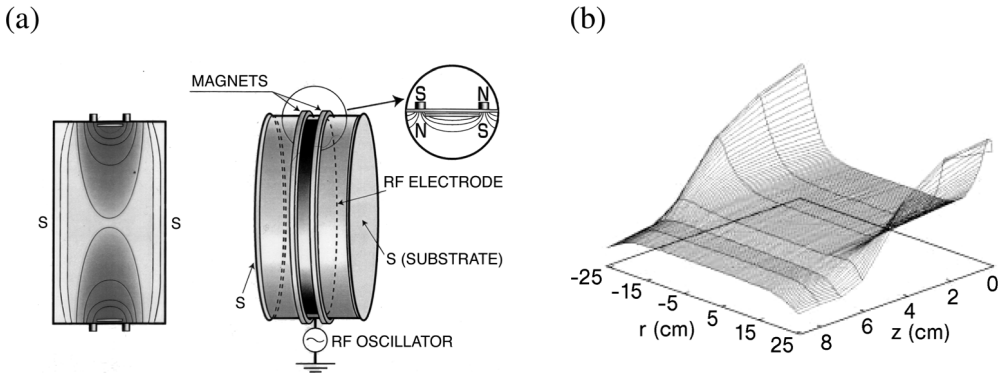


Fig. 1.2 Details of apparatus proposed for ECR plasma production in plasma application.



**Fig. 1.3** (a) Schematic of MMT plasma production and (b) measured variation of radial plasma density profiles in the axial direction.

The plasma density is found to have a peak near the electrode and decreases in the direction toward the radial center. But, with an increase in  $z$  (axial distance from machine center), the plasma diffuses toward the radial center, flattening the radial density profile. This MMT rf discharge yields an almost uniform plasma in the radial region of 40 cm in diameter at  $z = 6.0$  cm where substrates (S) can be situated, as shown for argon pressure of  $1.0 \times 10^{-3}$  torr and rf power of 200 W in Fig. 1.3(b). Now we can produce a uniform plasma, the diameter of which is larger than 100 cm [6,7]. A feedback control is effective for meter-size uniform processing, where the signal due to the non-uniformity is used as a feedback signal to a small electrode for additional discharge to provide uniform processing.

The potential drop in front of the ring electrode is changed by varying the magnetic strength and configuration. Therefore we can control energies of ions toward substrates [8] and particle sputtering due to high-energy ions accelerated by the potential drop. In the experiment, we could find the condition where there is no appreciable sputtering from the electrode [9]. Figure 1.4 demonstrates the MMT plasma reactor developed by Hitachi Kokusai Electric Inc. for semiconductor manufacturing [10].

### 1.1.2

#### Under Medium Gas Pressure (0.1–10 torr)

A parallel-plate rf discharge in this pressure range has been widely used for plasma production in applications. Multi-hollows formed in a cathode (rf powered electrode) are known to be effective for increasing the plasma density. A cathode with isolated hollows (CIH) (see Fig. 1.5(a)) is used in many cases. But, the discharge is often localized in the special hollow(s). There is also a possibility of dust particle trapping in the isolated hollows.

Here, a cathode with connected hollows (CCH) (see Fig. 1.5(b)) is employed to eliminate these problems in the CIH [11]. In this case, the hollows are connected

# MMT Plasma Reactor

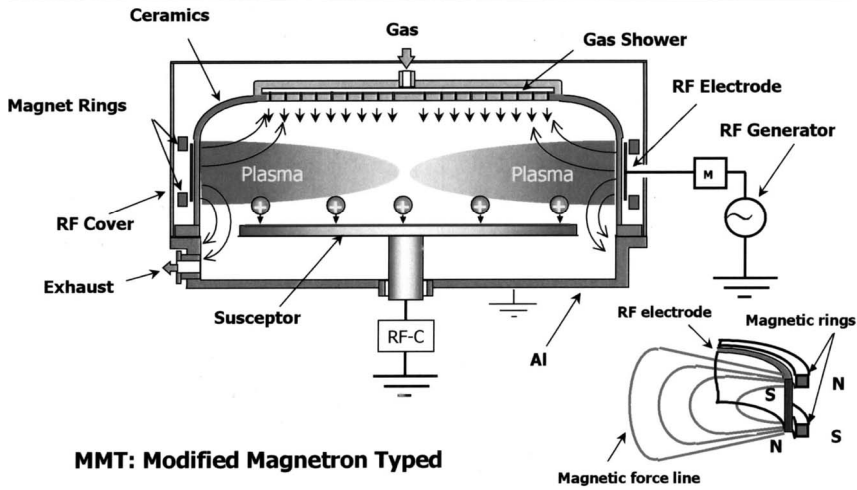


Fig. 1.4 MMT reactor used in plasma processing for semiconductor manufacturing (Hitachi Kokusai Electric Inc. [10]).

by ditches [3]. The CCH is topologically different from the CIH. Gas-feed holes are made in the bottoms of the hollows and/or between the hollows. An apparatus with the CCH is shown, together with photographs of (a) parallel-plate discharge and (b) CCH discharge, in Fig. 1.6. In the case of the CCH, the discharge brightness is enhanced and the plasma density is twice as high as that in the case of plane parallel-plate discharge at the same input rf power. The density has been confirmed to

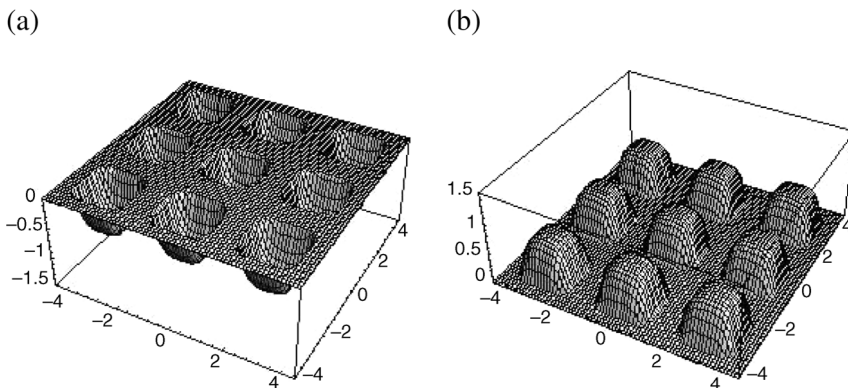


Fig. 1.5 Uneven electrodes: (a) concave-type electrode (CIH) and (b) convex-type electrode (CCH).

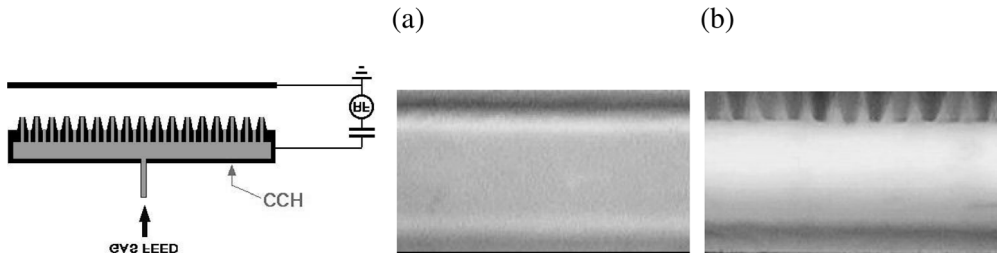


Fig. 1.6 Left: apparatus with CCH. (a) Parallel-plate discharge and (b) CCH discharge.

increase with an increase in the rf power, without localization of the discharge, yielding a uniform plasma for large-scaled processing.

### 1.1.3

#### Under High (Atmospheric) Gas Pressure (> 10 torr)

Plasma processing using atmospheric plasmas is now quite useful for various kinds of applications. So-called “barrier discharges” are well known as a method of plasma production under high (atmospheric) gas pressure. Electrodes for this discharge are shown in Fig. 1.7(a), where one of the electrodes is covered by dielectric material. An equivalent circuit for this situation of discharge is shown in Fig. 1.7(b).

We have proposed a quite simple method of plasma production under high (atmospheric) gas pressure. Pole-type electrodes, which are coupled with external capacitors, are set near a metal plate. This arrangement is just a direct realization of the circuit in Fig. 1.6(b). This is called capacity-coupled multi-discharge (CCMD) [12]. Under some conditions, the pole length is set to be so short that the electrodes are almost small plates. Being different from the barrier discharges, the discharge power of the CCMD can be externally controlled to increase by increasing the capacity of the capacitors. Measurements have proved that the CCMD provides high-power discharges, suggesting new possibilities for plasma applications in the high (atmospheric) pressure range.

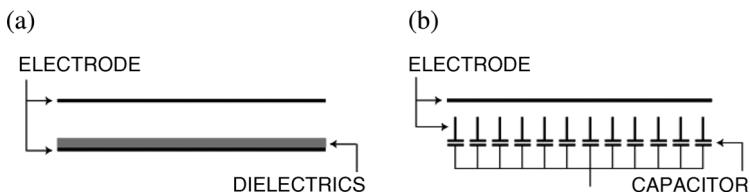


Fig. 1.7 (a) Typical barrier-discharge electrodes and (b) electrodes for capacitor-coupled multidischarge (CCMD).