Advanced Plasma Technology

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

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The Editors

Prof. Riccardo d'Agostino
Dipartimento di Chimica
Università di Bari
Italien

Prof. Pietro Favia
Dipartimento di Chimica
Università di Bari
Italien

Prof. Yoshinobu Kawai
Kyushu University
Engineering Sciences
Fukuoka, Japan

Prof. Hideo Ikegami
Nagoya, Japan

Prof. Noriyoshi Sato
Graduate School of Engineering
Tohoku University
Sendai, Japan

Prof. F. Arefi-Khonsari
Laboratoire de Genie des
Procedes Plasmas
Paris, Frankreich

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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.

October 2007

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

List of Contributors

E. Amanatides
Plasma Technology Lab
Department Chemical Engineering
University of Patras
P.O. Box 1407
26504 Patras
Greece

Akira Ando
Department of Electrical Engineering
Tohoku University
6-6-05 Aoba-yama
Aoba
Sendai 980-8579
Japan

Farzaneh Arefi-Khonsari
Laboratoire de Génie des Procédés
Plasma et Traitements de Surface
Université Pierre et Marie Curie
ENSCP
11 rue Pierre et Marie Curie
75231 Paris cedex 05
France

Natalia Babaeva
Department of Electrical and Computer
Engineering
Iowa State University
Ames, IA 50011
USA

Jen-Shih Chang
McMaster University (Professor
Emeritus)
NRB 118 Hamilton
Ontario L8S 4M1
Canada

Francis F. Chen
Electrical Engineering Department
University of California
Los Angeles, CA 90095-1594
USA

Vittorio Colombo
Department of Mechanical Engineering
(DIEM) and Research Center for
Applied Mathematics (CIRAM)
University of Bologna
Via Saragozza 8
40123 Bologna
Italy

Pascal Colpo
European Commission
Joint Research Centre
Institute for Health and Consumer
Protection
21020 Ispra (VA)
Italy

Riccardo d'Agostino
Department of Chemistry
University of Bari
via Orabona 4
70126 Bari
Italy

Sarah E. Dickson
Department of Civil Engineering
McMaster University
Hamilton
Ontario L8S 4B2
Canada

Monica B. Emelko
Department of Civil and
Environmental Engineering
University of Waterloo
200 University Avenue West
Waterloo
Ontario N2L 3G1
Canada

R. Engeln
Department of Applied Physics
Eindhoven University of Technology
P.O. Box 513
5600 MB Eindhoven
The Netherlands

F. Fanelli
Department of Chemistry
University of Bari
via Orabona 4
70126 Bari
Italy

Pietro Favia
Department of Chemistry
University of Bari
via Orabona 4
70126 Bari
Italy

F. Fracassi
Department of Chemistry
University of Bari
via Orabona 4
70126 Bari
Italy

Emanuele Ghedini
Department of Mechanical Engineering
(DIEM) and Research Center for
Applied Mathematics (CIRAM)
University of Bologna
Via Saragozza 8
40123 Bologna
Italy

Roberto Gristina
Department of Chemistry
University of Bari
via Orabona 4
70126 Bari
Italy

Yiping Guo
Department of Civil Engineering
McMaster University
Hamilton
Ontario L8S 4B2
Canada

Marina Hasiwa
European Commission
Joint Research Centre
Institute for Health and Consumer
Protection
21020 Ispra (VA)
Italy

Kunihiko Hattori
Nippon Institute of Technology
Miyashiro-machi
Minami-saitama-gun
Saitama 345-8501
Japan

H. Huang
Department of Materials Engineering
The University of Tokyo
7-3-1
Hongo
Bunkyo-Ku
Tokyo 113-8656
Japan

Hideo Ikegami
National Institute for Fusion Science
Toki
Gifu 509-5292
Japan

Masaaki Inutake
Department of Electrical Engineering
Tohoku University
6-6-05 Aoba-yama
Aoba
Sendai 980-8579
Japan

Ryohei Itatani
601-1311 Daigo-Ohtakacho 11-18
Husimi-ku
Kyoto
Japan

Felipe Iza
Department of Electronic and Electrical Engineering
Pohang University of Science and Technology
Pohang 790-784
South Korea

M. Kambara
Department of Materials Engineering
The University of Tokyo
7-3-1
Hongo
Bunkyo-Ku
Tokyo 113-8656
Japan

Yoshinobu Kawai
Research Institute for Applied Mechanics
Kyushu University
Kasugakoen 6-1
Kasuga
Fukuoka 816-8580
Japan

W. M. M. Kessels
Department of Applied Physics
Eindhoven University of Technology
P.O. Box 513
5600 MB Eindhoven
The Netherlands

I. E. Kieft
Department of Biomedical Engineering
Eindhoven University of Technology
P.O. Box 513
5600 MB Eindhoven
The Netherlands

Sung Jin Kim
Department of Electronic and Electrical Engineering
Pohang University of Science and Technology
Pohang 790-784
South Korea

Kazunori Koga
Graduate School of Information Science & Electrical Engineering
Kyushu University
Fukuoka 812-8581
Japan

Masuhiro Kogoma
Department of Chemistry
Faculty of Science and Technology
Sophia University
7-1 Kioicho
Chiyoda-ku 102-8554
Japan

Ondřej Kylián
European Commission
Joint Research Centre
Institute for Health and Consumer Protection
21020 Ispra (VA)
Italy

Sung Hee Lee
Department of Electronic and Electrical Engineering
Pohang University of Science and Technology
Pohang 790-784
South Korea

Hae June Lee
Busan National University
Busan 609-735
South Korea

Jae Ko Lee
Department of Electronic and Electrical Engineering
Pohang University of Science and Technology
Pohang 790-784
South Korea

Hiroshi Mashima
Nagasaki Research & Development Center
Mitsubishi Heavy Industries Ltd.
Fukahori
Nagasaki 851-0392
Japan

D. Mataras
Plasma Technology Lab
Department Chemical Engineering
University of Patras
P.O. Box 1407
26504 Patras
Greece

Akihisa Matsuda
Tokyo University of Science
2641 Yamazaki
Noda-shi
Chiba 278-8510
Japan

Andrea Mentrelli
Research Center for Applied Mathematics (CIRAM)
University of Bologna
Via Saragozza 8
40123 Bologna
Italy

Tarik Meziani
European Commission
Joint Research Centre
Institute for Health and Consumer Protection
21020 Ispra (VA)
Italy

Antonella Milella
Department of Chemistry
University of Bari
via Orabona 4
70126 Bari
Italy

Marina Nardulli
Department of Chemistry
University of Bari
via Orabona 4
70126 Bari
Italy

F. Palumbo
Institute of Inorganic Methodologies and Plasmas
IMIP-CNR
via Orabona 4
70126 Bari
Italy

François Rossi
European Commission
Joint Research Centre
Institute for Health and Consumer Protection
21020 Ispra (VA)
Italy

Eloisa Sardella
Department of Chemistry
University of Bari
via Orabona 4
70126 Bari
Italy

Noriyoshi Sato
Tohoku University (Professor Emeritus)
Kadan 4-17-113
Sendai 980-0815
Japan

D. C. Schram
Department of Applied Physics
Eindhoven University of Technology
P.O. Box 513
5600 MB Eindhoven
The Netherlands

Tsutae Shinoda
Fujitsu Laboratories Ltd.
64 Nishiwaki
Ohkubo-cho
Akashi 674-0054
Japan

Masaharu Shiratani
Graduate School of Information Science & Electrical Engineering
Kyushu University
Fukuoka 812-8581
Japan

D. W. Slaaf
Department of Biomedical Engineering
Eindhoven University of Technology
P.O. Box 513
5600 MB Eindhoven
The Netherlands

R. E. J. Sladek
Department of Biomedical Engineering
Eindhoven University of Technology
P.O. Box 513
5600 MB Eindhoven
The Netherlands

E. Stoffels
Department of Biomedical Engineering
Eindhoven University of Technology
P.O. Box 513
5600 MB Eindhoven
The Netherlands

Hiromu Takatsuka
Nagasaki Shipyard & Machinery Works
Mitsubishi Heavy Industries Ltd.
Isahaya
Nagasaki 854-0065
Japan

Yoshiaki Takeuchi
Nagasaki Research & Development Center
Mitsubishi Heavy Industries Ltd.
Fukahori
Nagasaki 851-0392
Japan

Kunihito Tanaka
Department of Chemistry
Faculty of Science and Technology
Sophia University
7-1 Kioicho
Chiyoda-ku 102-8554
Japan

M. Tatoulian
Laboratoire de Génie des Procédés
Plasma et Traitements de Surface
Université Pierre et Marie Curie
ENSCP
11 rue Pierre et Marie Curie
75231 Paris cedex 05
France

Hiroyuki Tobari
Japan Atomic Energy Agency
Naka
Ibaraki 311-0193
Japan

T. Trombetti
Department of Mechanical Engineering (DIEM)
University of Bologna
Via Saragozza 8
40123 Bologna
Italy

Kuniko Urashima
McMaster University (Professor Emeritus)
NRB 118 Hamilton
Ontario L8S 4M1
Canada

M. C. M. van de Sanden
Department of Applied Physics
Eindhoven University of Technology
P.O. Box 513
5600 MB Eindhoven
The Netherlands

M. A. M. J. van Zandvoort
Department of Biomedical Engineering
Eindhoven University of Technology
P.O. Box 513
5600 MB Eindhoven
The Netherlands

Yukio Watanabe
Kyushu University (Professor Emeritus)
Iki-Danchi
Fukuoka 819-0042
Japan

Yasuhiro Yamauchi
Nagasaki Shipyard & Machinery Works
Mitsubishi Heavy Industries Ltd.
Isahaya
Nagasaki 854-0065
Japan

T. Yoshida
Department of Materials Engineering
The University of Tokyo
7-3-1
Hongo
Bunkyo-Ku
Tokyo 113-8656
Japan

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 (~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.

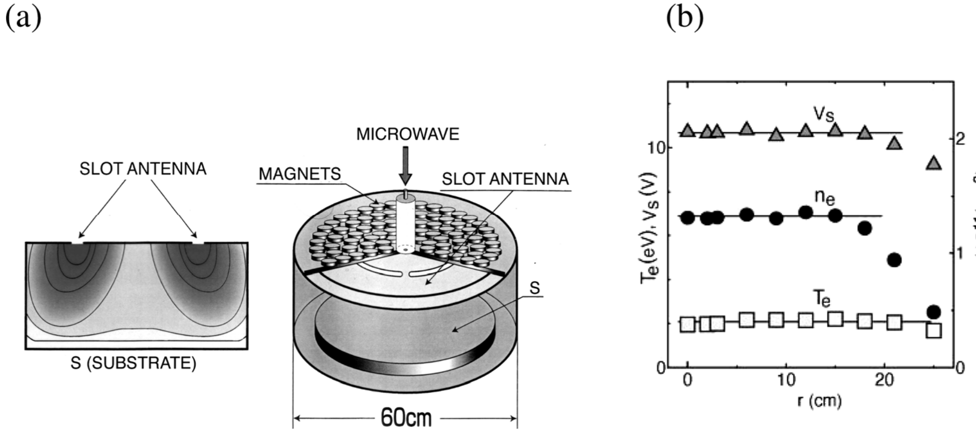

Fig. 1.1 (a) Schematic of ECR plasma production using a plane-slotted antenna with magnets and (b) radial profiles of plasma parameters measured at $z = 10$ cm.

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 $n_p \approx 1.3 \times 10^{11}\,\mathrm{cm}^{-3}$ 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 5.0×10^{-4}–5.0×10^{-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.

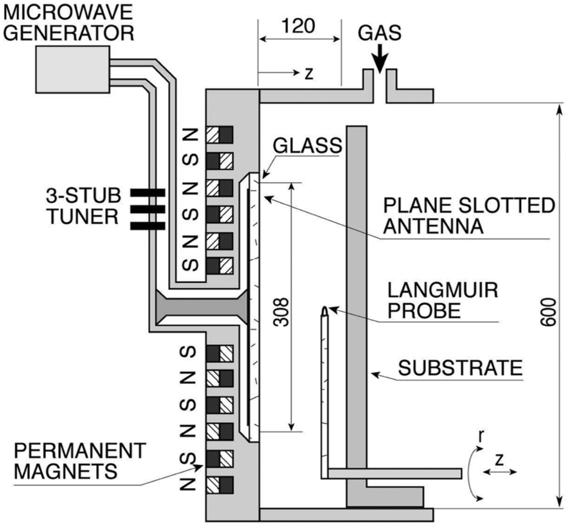

Fig. 1.2 Details of apparatus proposed for ECR plasma production in plasma application.

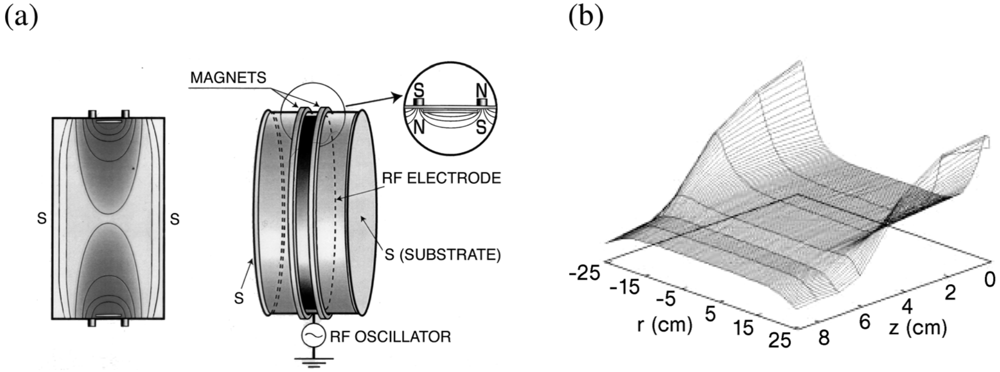

Fig. 1.3 (a) Schematic of MMT plasma production and (b) measured variation of radial plasma density profiles in the axial direction.

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 1.0×10^{-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

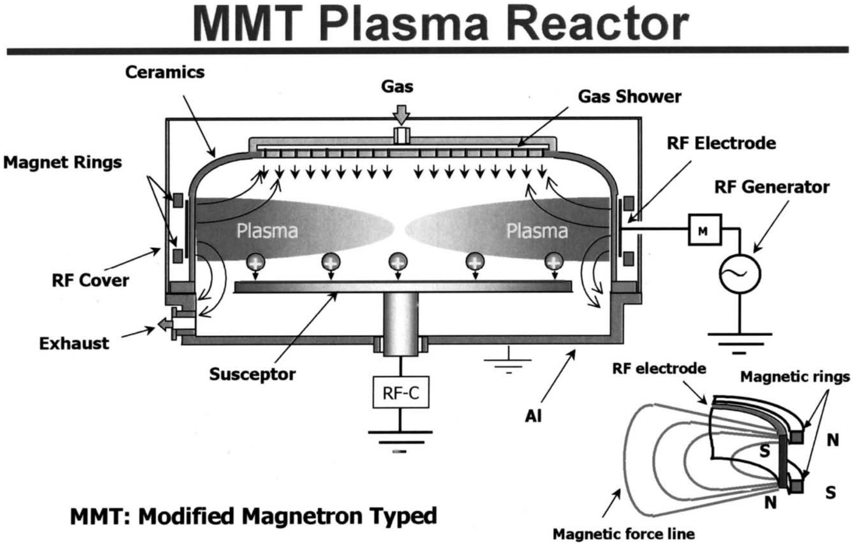

Fig. 1.4 MMT reactor used in plasma processing for semiconductor manufacturing (Hitachi Kokusai Electric Inc. [10]).

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

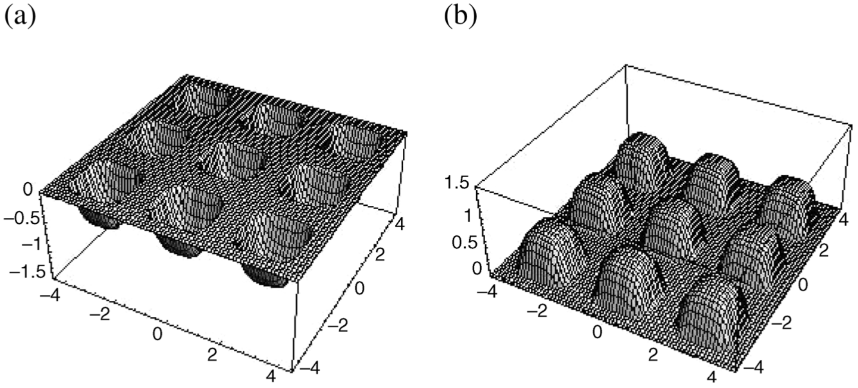

Fig. 1.5 Uneven electrodes: (a) concave-type electrode (CIH) and (b) convex-type electrode (CCH).

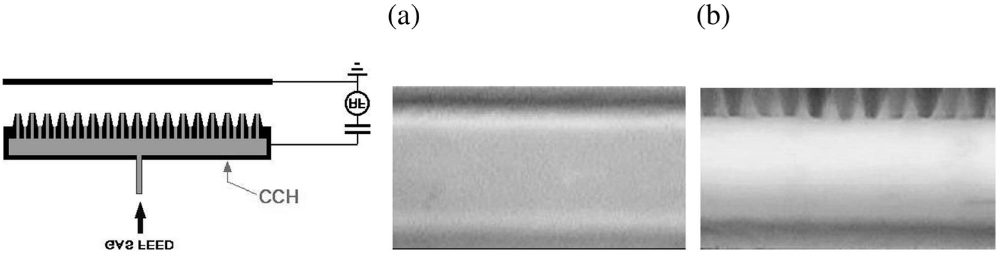

Fig. 1.6 Left: apparatus with CCH. (a) Parallel-plate discharge and (b) CCH discharge.

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.

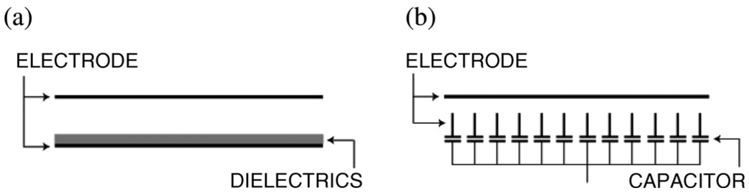

Fig. 1.7 (a) Typical barrier-discharge electrodes and (b) electrodes for *capacitor-coupled multidischarge* (CCMD).