Materials Processing of Semiconductor (반도체재료공정학)

Time: Tuesday (화) (10:00-13:00), Place: 대학원.토건관 418강의실

Lecture 1

Introduction to the Course

MAE9016 Materials Processing of Semiconductor

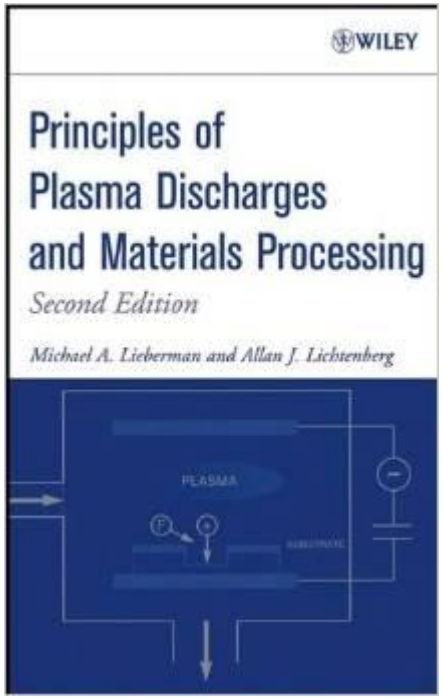
Textbook: M.A. Lieberman and A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, 2nd ed. (John Wiley, New York, 2005).

References:

1. **F.F. Chen, Introduction to Plasma Physics and Controlled Fusion, Vol. 1, 2nd ed. (Plenum Press, 1984).**
2. **F.F. Chen and J.P. Chang, Lecture Notes on Principles of Plasma Processing (Plenum/Kluwer Publishers, 2003)**
3. **PTSG Codes and Notes, Plasma Theory and Simulation Group, formerly at UC Berkeley, now at Michigan State University (http://ptsg.egr.msu.edu)**
4. **Prof. ChinWook Chung's Lecture Notes on "Material Processing of Semiconductors".**
5. **Literature Papers.**

Evaluation: Attendance and Home Work: 40%, Midterm Exam: 30%, Final Report: 30%.

Introduction to Textbook & References



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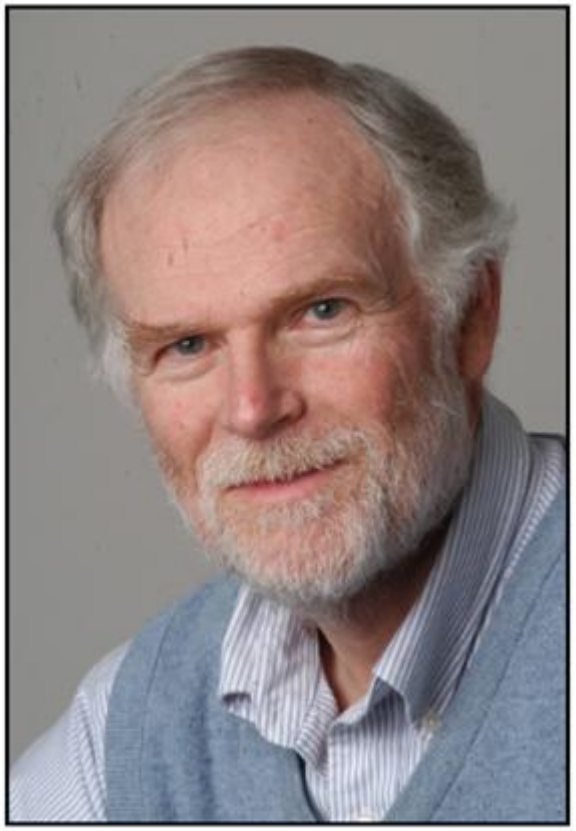
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RESEARCH
Research Interests
Talks
Resume
List of Publications

TEACHING
Courses

Textbook: *Regular and Chaotic Dynamics*

Textbook: *Principles of Plasma Discharges and Materials Processing*
First Edition Errata: download pdf file



http://www.eecs.berkeley.edu/~lieber/

Introduction to Textbook & References

http://www.seas.ucla.edu/~ffchen/

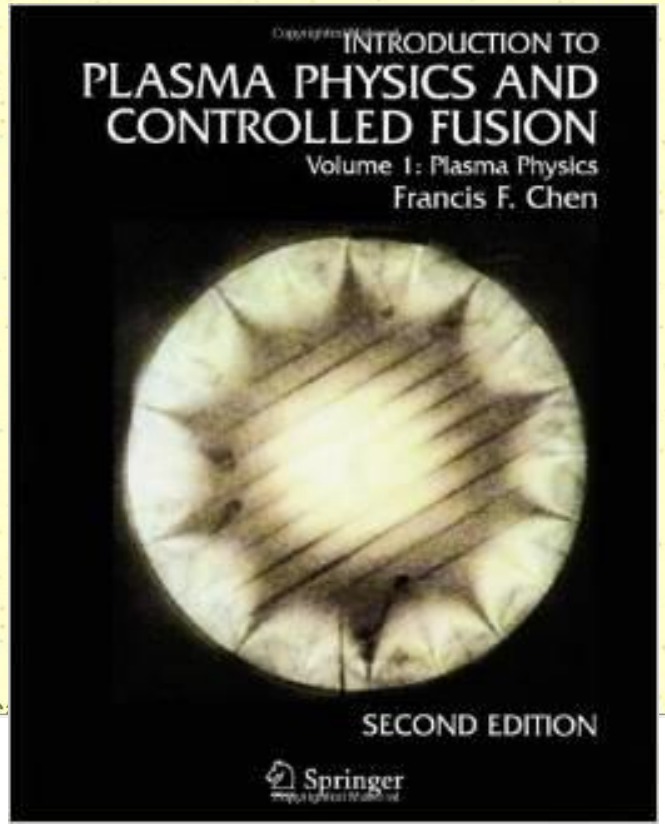
F.F. Chen's Home Page

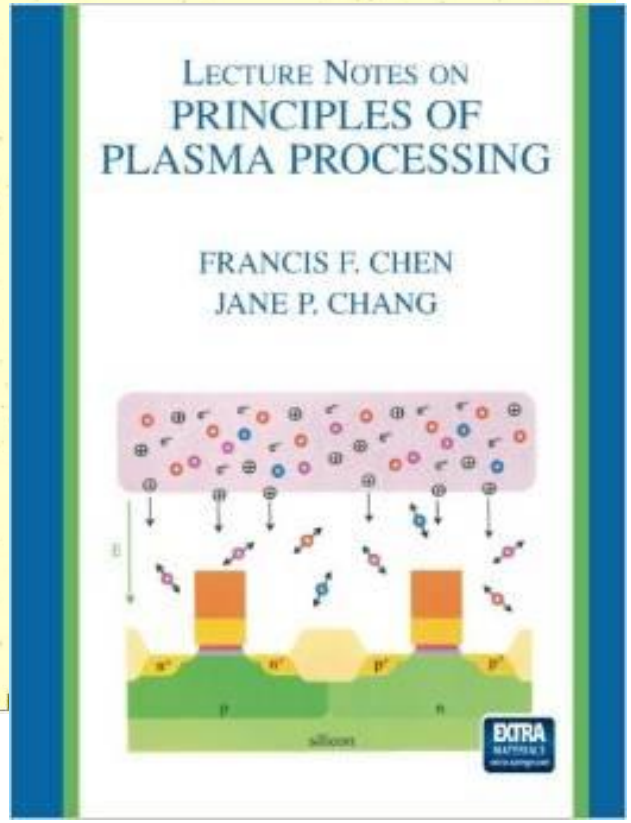
[Home] [Short Biography] [Research] [Courses] [Publications]



Francis F. Chen, *Professor Emeritus*
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Prof. Chen is a plasma physicist with a c





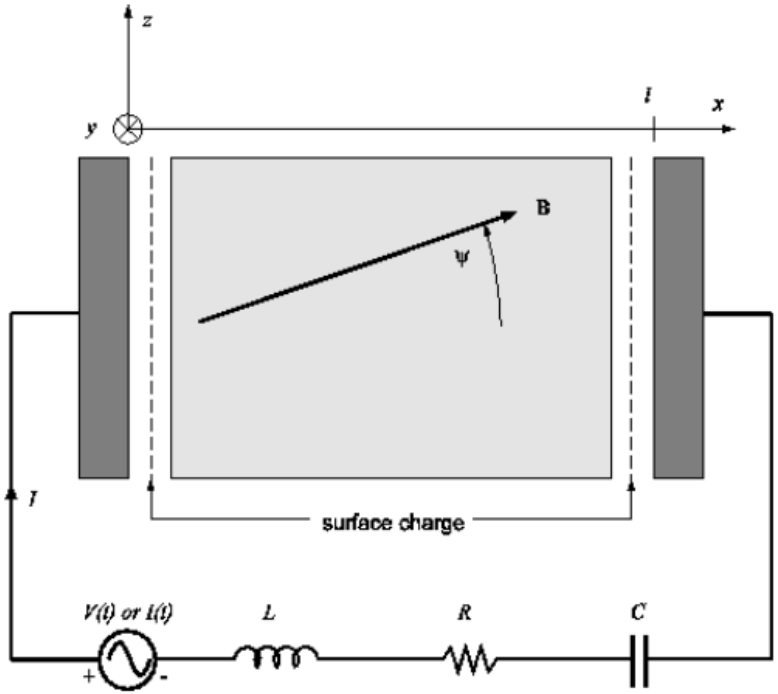
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http://ptsg.egr.msu.edu/

The Plasma Theory and Simulation Group



CHARLES KENNEDY BIRDSALL
EECS, UCB





John P. Verboncoeur
NE, UCB

Introduction (Motivation)

Why study plasma processing?

Because we can't get along without computer chips and mobile phones these days. About half the steps in making a semiconductor circuit require a plasma, and plasma machines account for most of the equipment cost in a "fab." Designers, engineers, and technicians need to know how a plasma behaves. These machines have to be absolutely reliable, because many millions of transistors have to be etched properly on each chip. It is amazing that this can be done at all; improvements will certainly require more plasma expertise. High-temperature plasmas have been studied for decades in connection with controlled fusion; that is, the production of electric power by creating miniature suns on the earth.

F.F. Chen and J.P. Chang, Lecture Notes on Principles of Plasma Processing (Plenum/Kluwer Publishers, 2003)

Introduction (Motivation)

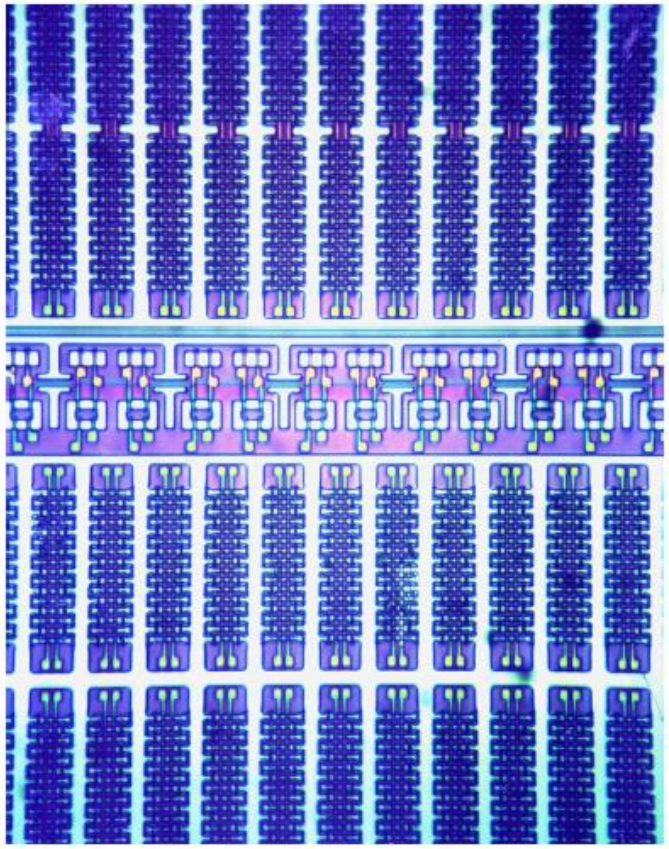
Why study plasma processing?

The low-temperature plasmas used in manufacturing are more complicated because they are not fully ionized; there are neutral atoms and many collisions. For many years, plasma sources were developed by trial and error, there being little understanding of how these devices worked. With the vast store of knowledge built up by the fusion effort, the situation is changing. Partially ionized, radiofrequency plasmas are being better understood, particularly with the use of computer simulation. Low-temperature plasma physics is becoming a real science. This is the new frontier. We hope you will join in the exploration of it.

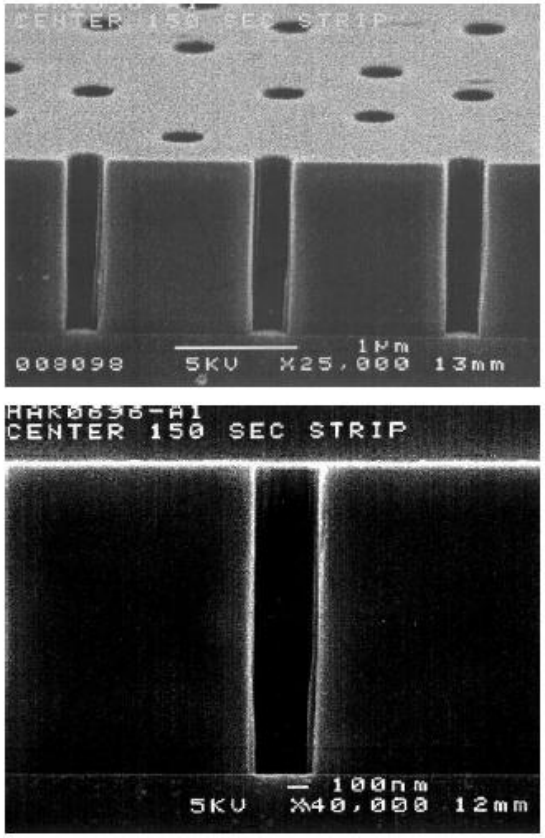
F.F. Chen and J.P. Chang, Lecture Notes on Principles of Plasma Processing (Plenum/Kluwer Publishers, 2003)

Introduction (Motivation)

Why study plasma processing?



A small section of a memory chip.



Straight holes like these can be etched only with plasmas

F.F. Chen and J.P. Chang, Lecture Notes on Principles of Plasma Processing (Plenum/Kluwer Publishers, 2003)

Introduction (Motivation)

Chap 1

1 INTRODUCTION 1

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M.A. Lieberman and A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, 2nd ed. (John Wiley, New York, 2005).

Introduction (Motivation)

Materials Processing

Chemically reactive plasma discharges are widely used to modify the surface properties of materials. Plasma processing technology is vitally important to several of the largest manufacturing industries in the world. Plasma-based surface processes are indispensable for manufacturing the very large scale integrated circuits (ICs) used by the electronics industry. Such processes are also critical for the aerospace, automotive, steel, biomedical, and toxic waste management industries. Materials and surface structures can be fabricated that are not attainable by any other commercial method, and the surface properties of materials can be modified in unique ways.

M.A. Lieberman and A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, 2nd ed. (John Wiley, New York, 2005).

Introduction (Motivation)

Materials Processing

For example, 0.2-mm-wide, 4-mm-deep trenches can be etched into silicon films or substrates (Fig. 1.1). A human hair is 50–100 mm in diameter, so hundreds of these trenches would fit endwise within a human hair. Unique materials such as diamond films and amorphous silicon for solar cells have also been produced, and plasma based hardening of surgically implanted hip joints and machine tools have extended their working lifetimes manyfold.

M.A. Lieberman and A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, 2nd ed. (John Wiley, New York, 2005).

Introduction (Motivation)

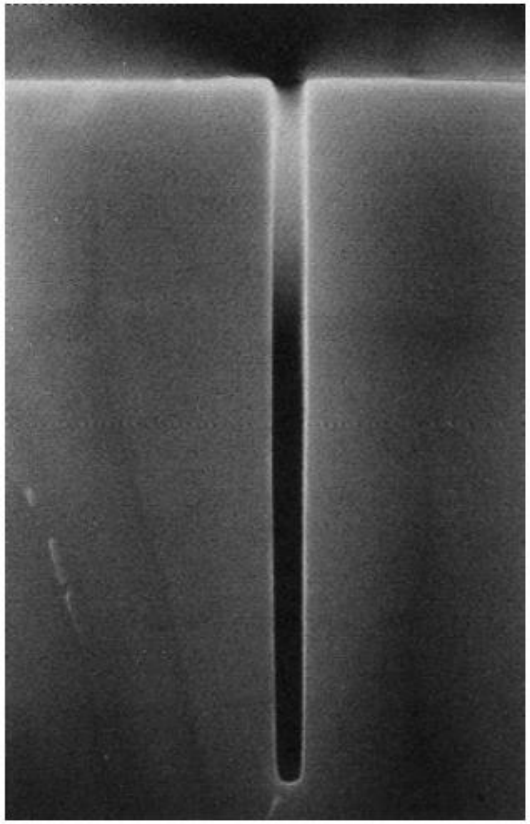


FIGURE 1.1. Trench etch (0.2 μm wide by 4 μm deep) in single-crystal silicon, showing the extraordinary capabilities of plasma processing; such trenches are used for device isolation and charge storage capacitors in integrated circuits.

M.A. Lieberman and A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, 2nd ed. (John Wiley, New York, 2005).

Introduction (Motivation)

Materials Processing

It is instructive to look closer at integrated circuit fabrication, which is the key application that we describe in this book. As a very incomplete list of plasma processes, argon or oxygen discharges are used to sputter-deposit aluminum, tungsten, or high-temperature superconducting films; oxygen discharges can be used to grow SiO_2 films on silicon; SiH_2Cl_2/NH_3 and $Si(OC_2H_5)_4/O_2$ discharges are used for the plasma-enhanced chemical vapor deposition (PECVD) of Si_3N_4 and SiO_2 films, respectively; BF_3 discharges can be used to implant dopant (B) atoms into silicon; CF_4/Cl_2O_2 discharges are used to selectively remove silicon films; and oxygen discharges are used to remove photoresist or polymer films.

SiH_2Cl_2 : Dichlorosilane ; $Si(OC_2H_5)_4$: Tetraethoxysilane (TEOS); BF_3 : Boron trifluoride ;

M.A. Lieberman and A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, 2nd ed. (John Wiley, New York, 2005).

Introduction (Motivation)

Materials Processing

These types of steps (deposit or grow, dope or modify, etch or remove) are repeated again and again in the manufacture of a modern IC. They are the equivalent, on a micrometer-size scale, of centimeter-size manufacture using metal and components, bolts and solder, and drill press and lathe. For microfabrication of an IC, one-third of the tens to hundreds of fabrication steps are typically plasma based.

M.A. Lieberman and A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, 2nd ed. (John Wiley, New York, 2005).

Introduction (Motivation)

Materials Processing

Figure 1.2 shows a typical set of steps to create a metal film patterned with submicrometer features on a large area (300 mm diameter) wafer substrate. In (a), the film is deposited; in (b), a photoresist layer is deposited over the film; in (c), the resist is selectively exposed to light through a pattern; and in (d), the resist is developed, removing the exposed resist regions and leaving behind a patterned resist mask. In (e), this pattern is transferred into the film by an etch process; the mask protects the underlying film from being etched. In (f), the remaining resist mask is removed. Of these six steps, plasma processing is generally used for film deposition (a) and etch (e), and may also be used for resist development (d) and removal (f).

M.A. Lieberman and A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, 2nd ed. (John Wiley, New York, 2005).

Introduction (Motivation)

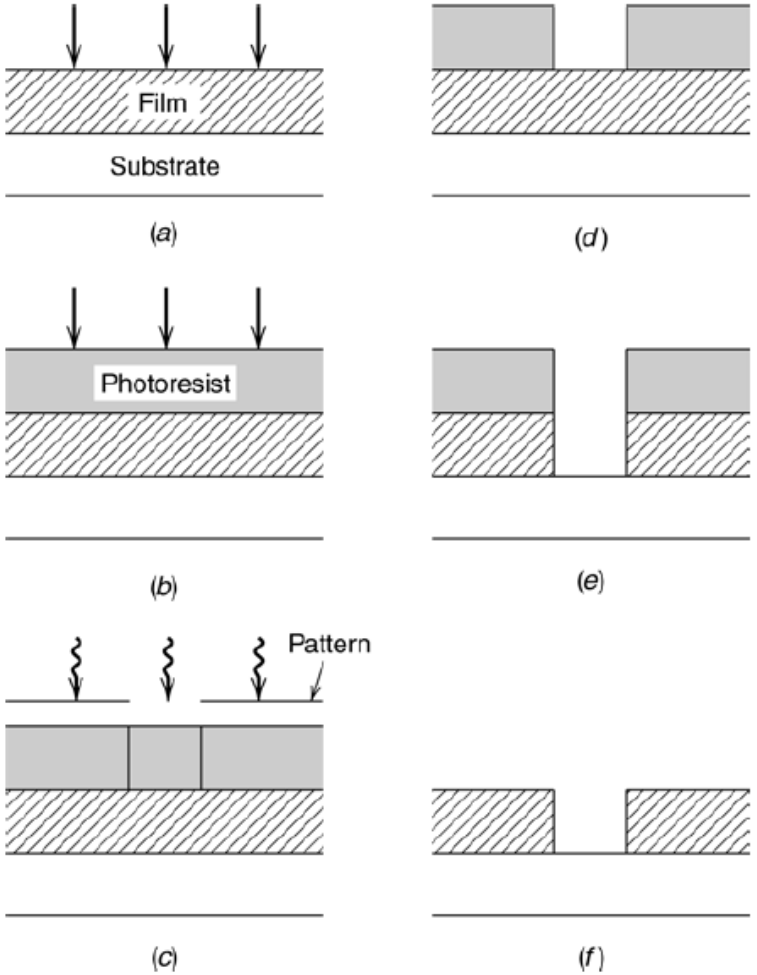


FIGURE 1.2. Deposition and pattern transfer in manufacturing an integrated circuit: (*a*) metal deposition; (*b*) photoresist deposition; (*c*) optical exposure through a pattern; (*d*) photoresist development; (*e*) anisotropic plasma etch; (*f*) remaining photoresist removal.

M.A. Lieberman and A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, 2nd ed. (John Wiley, New York, 2005).

Introduction (Motivation)

Materials Processing

The etch process in (e) is illustrated as leading to vertical sidewalls aligned with the resist mask; that is, the mask pattern has been faithfully transferred into the metal film. This can be accomplished by an etch process that removes material in the vertical direction only. The horizontal etch rate is zero. Such anisotropic etches are easily produced by plasma processing. On the other hand, one might imagine that exposing the masked film (d) to a liquid (or vapor phase) etchant will lead to the undercut isotropic profile shown in Figure 1.3a (compare to Fig. 1.2e), which is produced by equal vertical and horizontal etch rates.

M.A. Lieberman and A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, 2nd ed. (John Wiley, New York, 2005).

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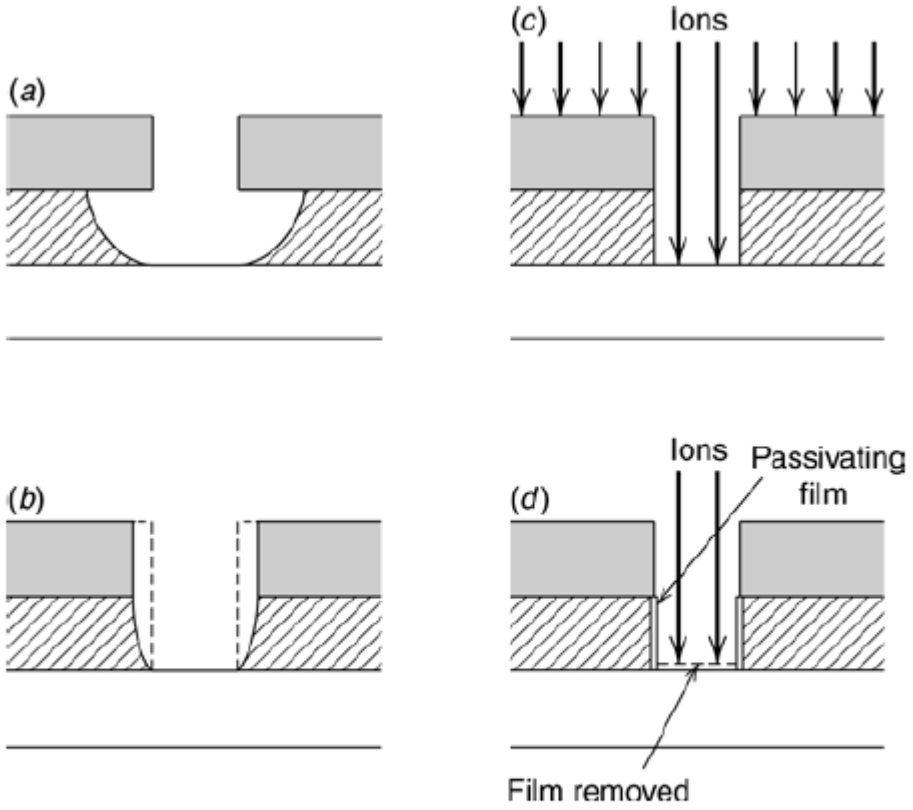


FIGURE 1.3. Plasma etching in integrated circuit manufacture: (*a*) example of isotropic etch; (*b*) sidewall etching of the resist mask leads to a loss of anisotropy in film etch; (*c*) illustrating the role of bombarding ions in anisotropic etch; (*d*) illustrating the role of sidewall passivating films in anisotropic etch.

M.A. Lieberman and A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, 2nd ed. (John Wiley, New York, 2005).

Introduction (Motivation)

Materials Processing

Many years ago, feature spacings (e.g., between trenches) were tens of micrometers, much exceeding required film thicknesses. Undercutting was then acceptable. This is no longer true with submicrometer feature spacings. The reduction in feature sizes and spacings makes anisotropic etch processes essential. In fact, strictly vertical etches are sometimes not desired; one wants controlled sidewall angles. Plasma processing is the only commercial technology capable of such control. Anisotropy is a critical process parameter in IC manufacture and has been a major force in driving the development of plasma processing technology.

M.A. Lieberman and A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, 2nd ed. (John Wiley, New York, 2005).

Introduction (Motivation)

Materials Processing

The etch process applied to remove the film in Figure 1.2d is shown in Figure 1.2e as not removing, either the photoresist or the underlying substrate. This selectivity is another critical process parameter for IC manufacture. Whereas wet etches have been developed having essentially infinite selectivity, highly selective plasma etch processes are not easily designed. Selectivity and anisotropy often compete in the design of a plasma etch process, with results as shown in Figure 1.3b. Compare this to the idealized result shown in Figure 1.2e.

M.A. Lieberman and A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, 2nd ed. (John Wiley, New York, 2005).

Introduction (Motivation)

Materials Processing

Assuming that film-to-substrate selectivity is a critical issue, one might imagine simply turning off the plasma after the film has been etched through. This requires a good endpoint detection system. Even then, variations in film thickness and etch rate across the area of the wafer imply that the etch cannot be stopped at the right moment everywhere. Hence, depending on the process uniformity, there is a need for some selectivity. These issues are considered further in Chapter 15.

M.A. Lieberman and A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, 2nd ed. (John Wiley, New York, 2005).

Introduction (Motivation)

Materials Processing

Here is a simple recipe for etching silicon using a plasma discharge. Start with an inert molecular gas, such as CF_4. Excite the discharge to sustain a plasma by electron–neutral dissociative ionization,

$$\text{Discharge : } e+CF_4 \rightarrow 2e+CF_3^+ +F$$

and to create reactive species by electron–neutral dissociation,

Reactive species by *e-n* dissociation

$$e+CF_4 \rightarrow e+F+CF_3 \rightarrow e+2F+CF_2$$

M.A. Lieberman and A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, 2nd ed. (John Wiley, New York, 2005).

Introduction (Motivation)

Materials Processing

The etchant F atoms react with the silicon substrate, yielding the volatile etch product SiF_4:

React with silicon

$$Si(s)+4F(g) \rightarrow SiF_4(g)$$

Here, s and g indicate solid and gaseous forms, respectively. Finally, the product is pumped away. It is important that CF_4 does not react with silicon, and that the etch product SiF_4 is volatile, so that it can be removed. This process etches silicon isotropically. For an anisotropic etch, there must be high-energy ion (CF_3^+) bombardment of the substrate.

M.A. Lieberman and A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, 2nd ed. (John Wiley, New York, 2005).

Introduction (Motivation)

Materials Processing

As illustrated in Figures 1.3c and d, energetic ions leaving the discharge during the etch bombard the bottom of the trench but do not bombard the sidewalls, leading to anisotropic etching by one of two mechanisms. Either the ion bombardment increases the reaction rate at the surface (Fig. 1.3c), or it exposes the surface to the etchant by removing passivating films that cover the surface (Fig. 1.3d).

M.A. Lieberman and A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, 2nd ed. (John Wiley, New York, 2005).

Introduction (Motivation)

Materials Processing

Similarly, Cl and Br atoms created by dissociation in a discharge are good etchants for silicon, F atoms and CF_2 molecules for SiO_2, O atoms for photoresist, and Cl atoms for aluminum. In all cases, a volatile etch product is formed. However, F atoms do not etch aluminum, and there is no known etchant for copper, because the etch products are not volatile at reasonable substrate temperatures.

$CF_2 \rightarrow SiO_2$

$O \rightarrow PR$ all products are volatile

$Cl \rightarrow Al$

M.A. Lieberman and A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, 2nd ed. (John Wiley, New York, 2005).

Introduction (Motivation)

Materials Processing

We see the importance of the basic physics and chemistry topics treated in this book: (1) plasma physics (Chapters 2, 4–6, and 18), to determine the electron and ion densities, temperatures, and ion bombardment energies and fluxes for a given discharge configuration; and (2) gas-phase chemistry and (3) surface physics and chemistry (Chapters 7 and 9), to determine the etchant densities and fluxes and the etch rates with and without ion bombardment. The data base for these fields of science is provided by (4) atomic and molecular physics, which we discuss in Chapters 3 and 8. We also discuss applications of equilibrium thermodynamics (Chapter 7) to plasma processing. The measurement and experimental control of plasma and chemical properties in reactive discharges is itself a vast subject. We provide brief introductions to some simple plasma diagnostic techniques throughout the text.

M.A. Lieberman and A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, 2nd ed. (John Wiley, New York, 2005).

Introduction (Motivation)

Materials Processing

We have motivated the study of the fundamentals of plasma processing by examining isotropic and anisotropic etches for IC manufacture. These are discussed in Chapter 15. Other characteristics motivate its use for deposition and surface modification. For example, a central feature of the low-pressure processing discharges that we consider in this book is that the plasma itself, as well as the plasma–substrate system, is not in thermal equilibrium.

M.A. Lieberman and A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, 2nd ed. (John Wiley, New York, 2005).

Introduction (Motivation)

Materials Processing

This enables substrate temperatures to be relatively low, compared to those required in conventional thermal processes, while maintaining adequate deposition or etch rates. Putting it another way, plasma processing rates are greatly enhanced over thermal processing rates at the same substrate temperature. For example, Si_3N_4 films can be deposited over aluminum films by PECVD, whereas adequate deposition rates cannot be achieved by conventional chemical vapor deposition (CVD) without melting the aluminum film. Chapter 16 gives further details.

M.A. Lieberman and A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, 2nd ed. (John Wiley, New York, 2005).

Introduction (Motivation)

Materials Processing

Particulates or "dust" can be a significant component in processing discharges and can be a source of substrate-level contamination in etch and deposition processes. One can also control dust formation in useful ways, for example, to produce powders of various sizes or to incorporate nanoparticles during deposition to modify film properties. Dusty plasmas are described in Chapter 17.

M.A. Lieberman and A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, 2nd ed. (John Wiley, New York, 2005).

Introduction (Motivation)

Materials Processing

The nonequilibrium nature of plasma processing has been known for many years, as illustrated by the laboratory data in Figure 1.4. In time sequence, this shows first, the equilibrium chemical etch rate of silicon in the XeF_2 etchant gas; next, the tenfold increase in etch rate with the addition of argon ion bombardment of the substrate, simulating plasma-assisted etching; and finally, the very low "etch rate" due to the physical sputtering of silicon by the ion bombardment alone.

M.A. Lieberman and A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, 2nd ed. (John Wiley, New York, 2005).

Introduction (Motivation)

Materials Processing

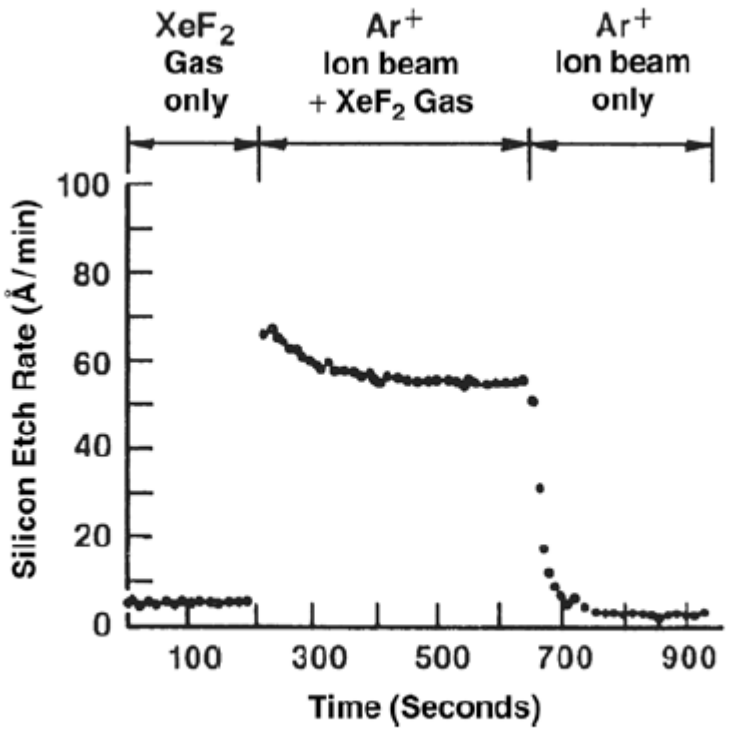


FIGURE 1.4. Experimental demonstration of ion-enhanced plasma etching. (Coburn and Winters, 1979.)

M.A. Lieberman and A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, 2nd ed. (John Wiley, New York, 2005).

Introduction (Motivation)

Materials Processing

Amore recent application is the use of plasma-immersion ion implantation (PIII) to implant ions into materials at dose rates that are tens to hundreds of times larger than those achievable with conventional (beam based) ion implantation systems. In PIII, a series of negative high-voltage pulses are applied to a substrate that is immersed directly into a discharge, thus accelerating plasma ions into the substrate. The development of PIII has opened a new implantation regime characterized by very high dose rates, even at very low energies, and by the capability to implant both large area and irregularly shaped substrates, such as flat panel displays or machine tools and dies. This is illustrated in Figure 1.5. Further details are given in Chapter 16.

M.A. Lieberman and A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, 2nd ed. (John Wiley, New York, 2005).

Introduction (Motivation)

Materials Processing

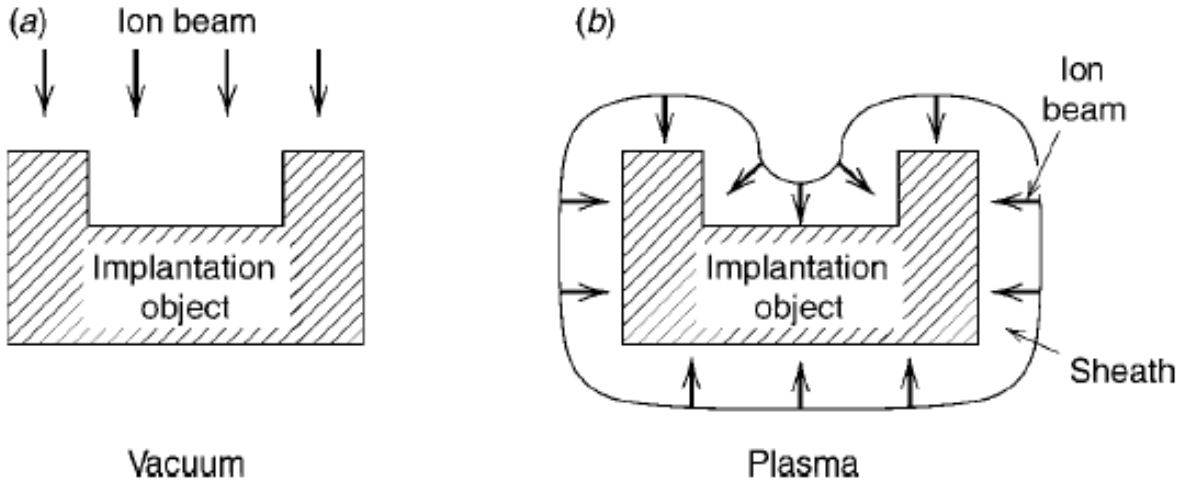


FIGURE 1.5. Illustrating ion implantation of an irregular object: (*a*) In a conventional ion beam implanter, the beam is electrically scanned and the target object is mechanically rotated and tilted to achieve uniform implantation; (*b*) in plasma-immersion ion implantation (PIII), the target is immersed in a plasma, and ions from the plasma are implanted with a relatively uniform spatial distribution.

M.A. Lieberman and A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, 2nd ed. (John Wiley, New York, 2005).

Introduction

Plasma?

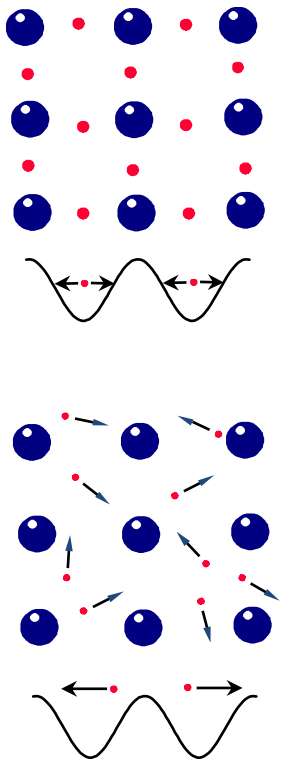
Plasmas are often called a fourth state of matter. As we know, a solid substance in thermal equilibrium generally passes into a liquid state as the temperature is increased at a fixed pressure. The liquid passes into a gas as the temperature is further increased. At a sufficiently high temperature, the molecules in the gas decompose to form a gas of atoms that move freely in random directions, except for infrequent collisions between atoms. If the temperature is further increased, then the atoms decompose into freely moving charged particles (electrons and positive ions), and the substance enters the plasma state.

M.A. Lieberman and A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, 2nd ed. (John Wiley, New York, 2005).

Introduction

Plasma?

4th State of Matter

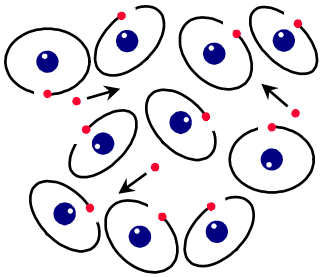


Insulator

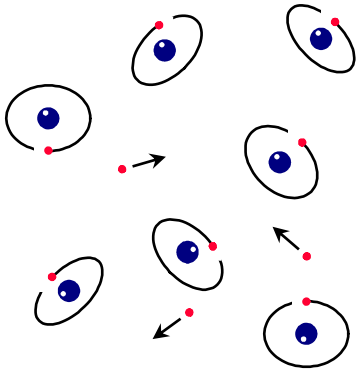
Conductor

Solid

Liquid

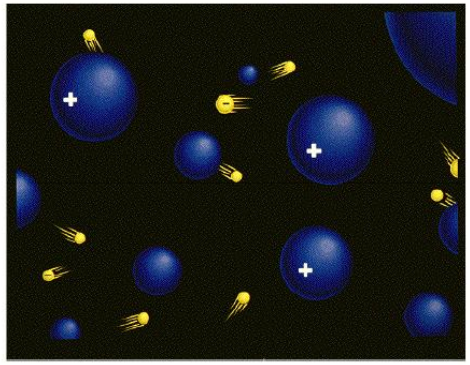


Gas



Plasma (ionized gas)

$n_i \sim n_e$



Ions and electrons make a plasma

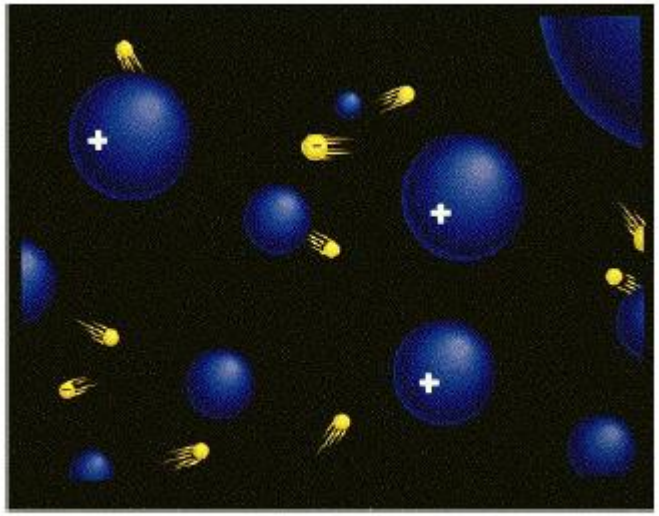
Prof. ChinWook Chung's Lecture Notes on "Material Processing of Semiconductors".

Heat

Introduction

Plasma?

Plasma is matter heated beyond its gaseous state, heated to a temperature so high that atoms are stripped of at least one electron in their outer shells, so that what remains are positive ions in a sea of free electrons.



Ions and electrons make a plasma

F.F. Chen and J.P. Chang, Lecture Notes on Principles of Plasma Processing (Plenum/Kluwer Publishers, 2003)

Introduction

Plasma?

A plasma is a collection of free charged particles moving in random directions that is, on the average, electrically neutral (see Fig. 1.6a). This book deals with weakly ionized plasma discharges, which are plasmas having the following features: (1) they are driven electrically; (2) charged particle collisions with neutral gas molecules are important; (3) there are boundaries at which surface losses are important; (4) ionization of neutrals sustains the plasma in the steady state; and (5) the electrons are not in thermal equilibrium with the ions.

M.A. Lieberman and A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, 2nd ed. (John Wiley, New York, 2005).

Introduction

Plasma?

A simple discharge is shown schematically in Figure 1.6b. It consists of a voltage source that drives current through a low-pressure gas between two parallel conducting plates or electrodes. The gas "breaks down" to form a plasma, usually weakly ionized, that is, the plasma density is only a small fraction of the neutral gas density. We describe some qualitative features of plasmas in this section; discharges are described in the following section.

M.A. Lieberman and A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, 2nd ed. (John Wiley, New York, 2005).

Introduction

Plasma?

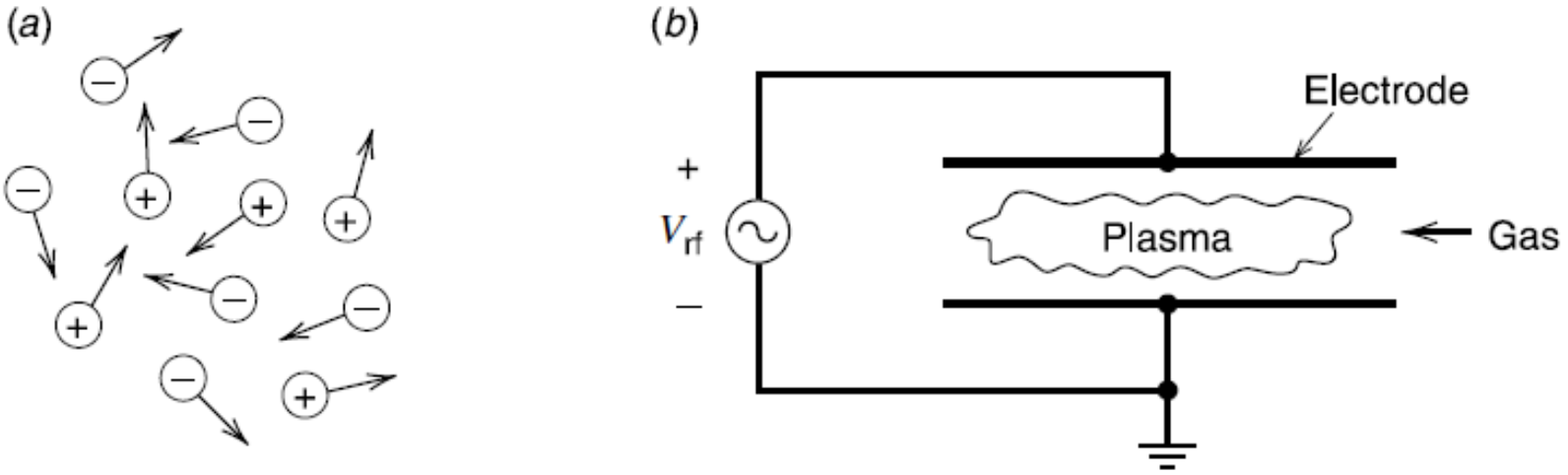


FIGURE 1.6. Schematic view of (*a*) a plasma and (*b*) a discharge.

M.A. Lieberman and A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, 2nd ed. (John Wiley, New York, 2005).

Introduction

Plasma?

This state is characterized by a common charged particle density $n_e \approx n_i \approx n$ particles/m^3 and, in equilibrium, a temperature $T_e = T_i = T$. The temperatures required to form plasmas from pure substances in thermal equilibrium range from roughly 4000 K for easy-to-ionize elements like cesium to 20,000 K for hard-to-ionize elements like helium. The fractional ionization of a plasma is

$$x_{iz} = \frac{n_i}{n_g + n_i}$$

where n_g is the neutral gas density. x_{iz} is near unity for fully ionized plasmas, and $x_{iz} << 1$ for weakly ionized plasmas.

M.A. Lieberman and A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, 2nd ed. (John Wiley, New York, 2005).

Introduction

Plasma?

Much of the matter in the universe is in the plasma state. This is true because stars, as well as most interstellar matter, are plasmas. Although stars are plasmas in thermal equilibrium, the light and heavy charged particles in low-pressure processing discharges are almost never in thermal equilibrium, either between themselves or with their surroundings. Because these discharges are electrically driven and are weakly ionized, the applied power preferentially heats the mobile electrons, while the heavy ions efficiently exchange energy by collisions with the background gas. Hence, $T_e >> T_i$ for these plasmas.

M.A. Lieberman and A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, 2nd ed. (John Wiley, New York, 2005).

Introduction

Plasma?

Figure 1.7 identifies different kinds of plasmas on a log n versus log Te diagram. There is an enormous range of densities and temperatures for both laboratory and space plasmas. Two important types of processing discharges are indicated on the figure. Low-pressure discharges are characterized by Te $\approx$ 1–10 V, Ti << Te, and n $\approx 10^{8}$–10^{13} cm^{-3}. These discharges are used as miniature chemical factories in which feedstock gases are broken into positive ions and chemically reactive etchants, deposition precursors, and so on, which then flow to and physically or chemically react at the substrate surface.

M.A. Lieberman and A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, 2nd ed. (John Wiley, New York, 2005).

Introduction

Plasma?

While energy is delivered to the substrate also, for example, in the form of bombarding ions, the energy flux is there to promote the chemistry at the substrate, and not to heat the substrate. The gas pressures for these discharges are low: $p \approx 1$ mTorr–1 Torr. These discharges and their use for processing are the principal subject of this book. We give the quantitative framework for their analysis in Chapter 10.

M.A. Lieberman and A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, 2nd ed. (John Wiley, New York, 2005).

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Plasma?

High-pressure arc discharges are also used for processing. These discharges have Te ≈ 0.1–2 V and n ≈ 10^{14}–10^{19} cm^{-3}, and the light and heavy particles are more nearly in thermal equilibrium, with Ti ≲ Te. These discharges are used mainly to deliver heat to the substrate, for example, to increase surface reaction rates, to melt, sinter, or evaporate materials, or to weld or cut refractory materials. Operating pressures are typically near atmospheric pressure (760 Torr). High-pressure discharges of this type are beyond the scope of this book.

M.A. Lieberman and A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, 2nd ed. (John Wiley, New York, 2005).

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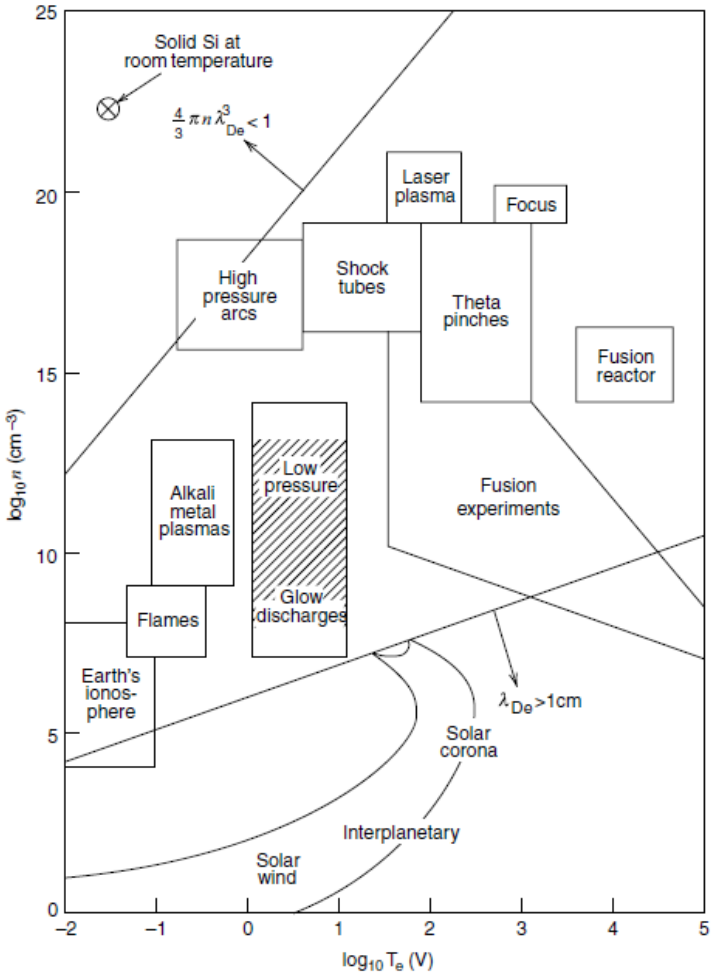


FIGURE 1.7. Space and laboratory plasmas on a log n versus log T_e diagram (after Book, 1987). λ_{De} is defined in Section 2.4.

M.A. Lieberman and A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, 2nd ed. (John Wiley, New York, 2005).

Introduction

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Figure 1.8 shows the densities and temperatures (or average energies) for various species in a typical rf-driven capacitively coupled low-pressure discharge; for example, for silicon etching using CF_4, as described in Section 1.1. We see that the feedstock gas, etchant atoms, etch product gas, and plasma ions have roughly the same temperature, which does not exceed a few times room temperature (0.026 V). The etchant F and product SiF4 densities are significant fractions of the CF_4 density, but the fractional ionization is very low: $n_i \sim 10^{-5} n_g$. The electron temperature T_e is two orders of magnitude larger than the ion temperature T_i.

M.A. Lieberman and A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, 2nd ed. (John Wiley, New York, 2005).

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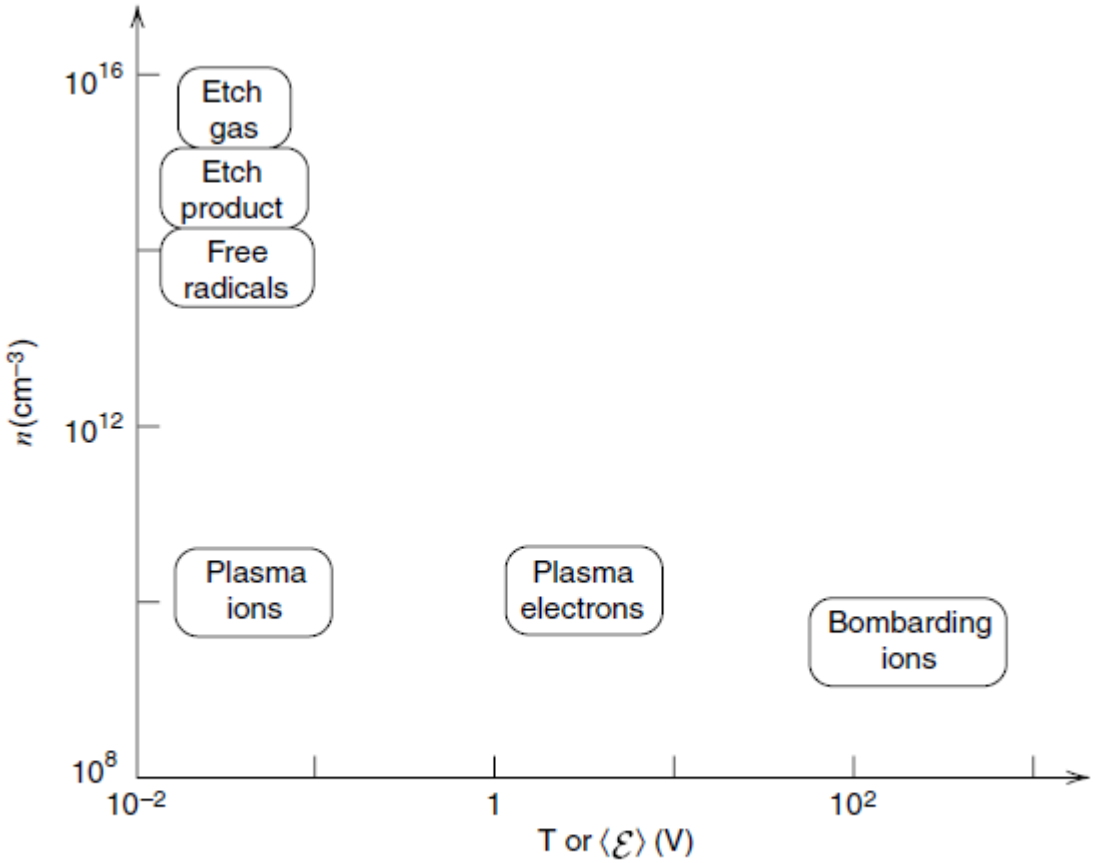


FIGURE 1.8. Densities and energies for various species in a low-pressure capacitive rf discharge.

M.A. Lieberman and A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, 2nd ed. (John Wiley, New York, 2005).

Introduction

Sheath?

However, we note that the energy of ions bombarding the substrate can be 100–1000 V, much exceeding T_e. The acceleration of low-temperature ions across a thin sheath region where the plasma and substrate meet is central to all processing discharges. We describe this qualitatively below and quantitatively in later chapters.

M.A. Lieberman and A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, 2nd ed. (John Wiley, New York, 2005).

Introduction

Plasma?

Although n_i and n_e may be five orders of magnitude lower that n_g, the charged particles play central roles in sustaining the discharge and in processing. Because $T_e >> T_i$, it is the electrons that dissociate the feedstock gas to create the free radicals, etchant atoms, and deposition precursors, required for the chemistry at the substrate. Electrons also ionize the gas to create the positive ions that subsequently bombard the substrate. As we have seen, energetic ion bombardment can increase chemical reaction rates at the surface, clear inhibitor films from the surface, and physically sputter materials from or implant ions into the surface.

M.A. Lieberman and A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, 2nd ed. (John Wiley, New York, 2005).

Introduction

Plasma?

T_e is generally less than the threshold energies E_{diss} or E_{iz} for dissociation and ionization of the feedstock gas molecules. Nevertheless, dissociation and ionization occur because electrons have a distribution of energies. Letting $g_e(E)\,dE$ be the number of electrons per unit volume with energies lying between E and $E + dE$, then the distribution function $g_e(E)$ is sketched in Figure 1.9. Electrons having energies below E_{diss} or E_{iz} cannot dissociate or ionize the gas. We see that dissociation and ionization are produced by the high-energy tail of the distribution.

M.A. Lieberman and A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, 2nd ed. (John Wiley, New York, 2005).

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Plasma?

Although the distribution is sketched in the figure as if it were Maxwellian at the bulk electron temperature Te, this may not be the case. The tail distribution might be depressed below or enhanced above a Maxwellian by electron heating and electron–neutral collision processes. Two temperature distributions are sometimes observed, with T_e for the bulk electrons lower than T_h for the energetic electron tail. Non-Maxwellian distributions can only be described using the kinetic theory of discharges, which we introduce in Chapter 18.

M.A. Lieberman and A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, 2nd ed. (John Wiley, New York, 2005).

Introduction

Plasma?

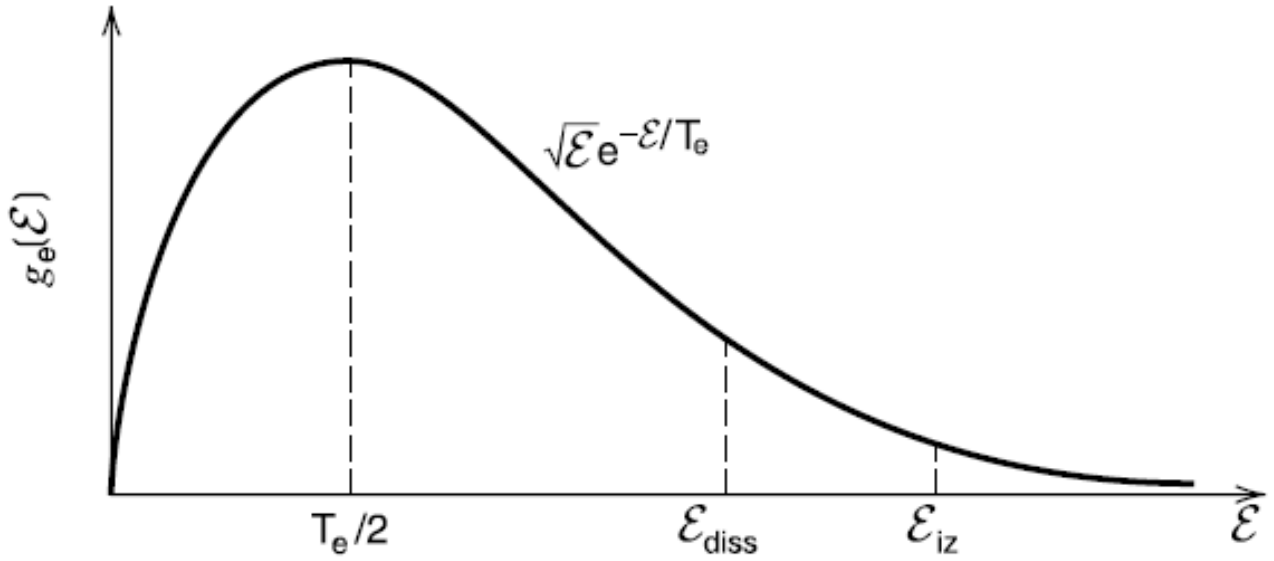


FIGURE 1.9. Electron distribution function in a weakly ionized discharge.

M.A. Lieberman and A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, 2nd ed. (John Wiley, New York, 2005).

Introduction

Sheath?

Plasmas, which are quasi-neutral (ni ≈ ne), are joined to wall surfaces across thin positively charged layers called sheaths. To see why, first note that the electron thermal velocity $(eT_e/m)^{1/2}$ is at least 100 times the ion thermal velocity $(eT_i/M)^{1/2}$ because $m/M << 1$ and $Te \gtrsim Ti$. (Here, T_e and T_i are given in units of volts.) Consider a plasma of width l with $n_e = n_i$ initially confined between two grounded ($\Phi = 0$) absorbing walls (Fig. 1.10a). Because the net charge density $\rho = e(n_i - n_e)$ is zero, the electric potential Φ and the electric field E_x is zero everywhere. Hence, the fast-moving electrons are not confined and will rapidly be lost to the walls. On a very short timescale, however, some electrons near the walls are lost, leading to the situation shown in Figure 1.10b.

M.A. Lieberman and A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, 2nd ed. (John Wiley, New York, 2005).

Introduction

Sheath?

Thin ($s << l$) positive ion sheaths form near each wall in which $n_i >> n_e$. The net positive ρ within the sheaths leads to a potential profile $\Phi(x)$ that is positive within the plasma and falls sharply to zero near both walls. This acts as a confining potential "valley" for electrons and a "hill" for ions because the electric fields within the sheaths point from the plasma to the wall. Thus the force $-e E_x$ acting on electrons is directed into the plasma; this reflects electrons traveling toward the walls back into the plasma. Conversely, ions from the plasma that enter the sheaths are accelerated into the walls. If the plasma potential (with respect to the walls) is V_p, then we expect that V_p a few T_e in order to confine most of the electrons. The energy of ions bombarding the walls is then $E_i \sim$ a few T_e. Charge uncovering is treated quantitatively in Chapter 2, and sheaths in Chapter 6.

M.A. Lieberman and A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, 2nd ed. (John Wiley, New York, 2005).

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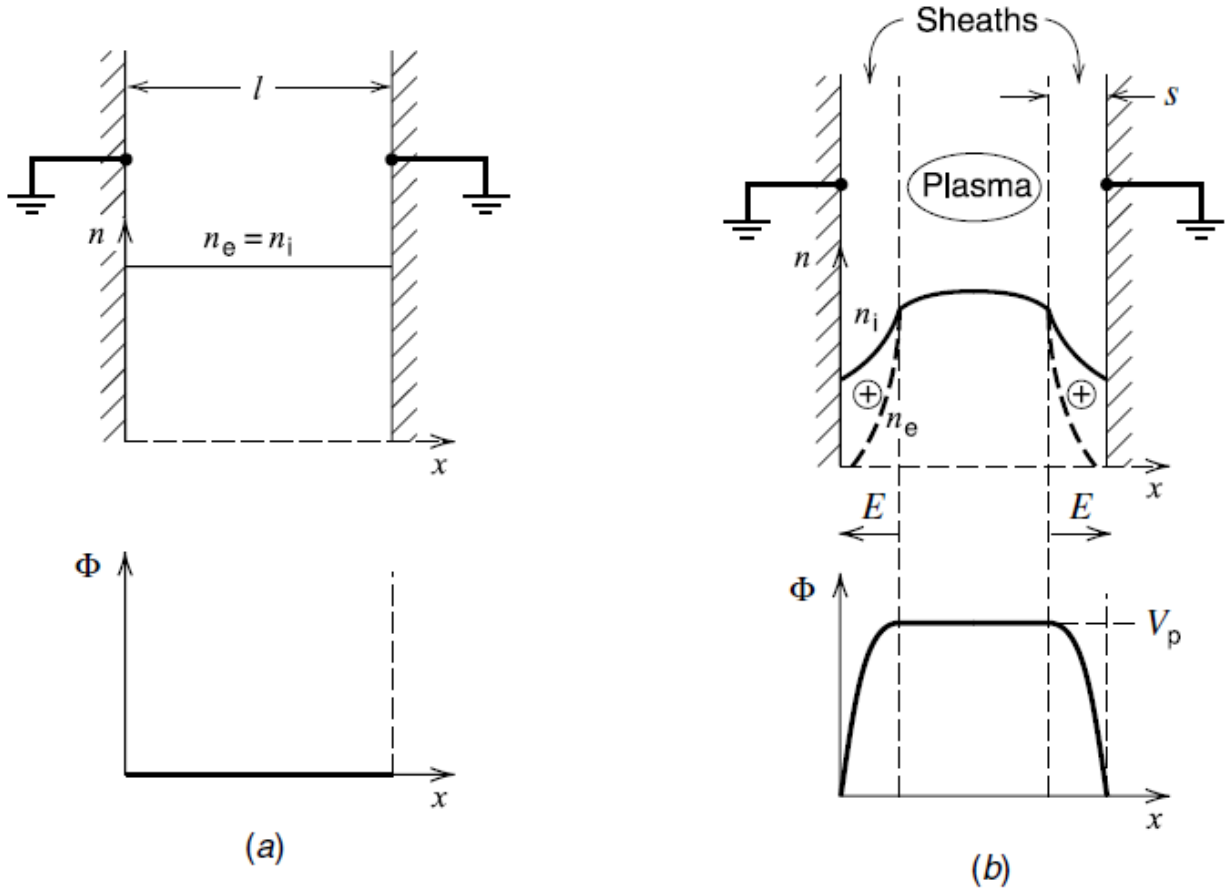


FIGURE 1.10. The formation of plasma sheaths: (*a*) initial ion and electron densities and potential; (*b*) densities, electric field, and potential after formation of the sheath.

M.A. Lieberman and A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, 2nd ed. (John Wiley, New York, 2005).

Introduction

Sheath?

Figure 1.11 shows sheath formation as obtained from a particle-in-cell (PIC) plasma simulation. We use PIC results throughout this book to illustrate various discharge phenomena. In this simulation, the left wall is grounded, the right wall is floating (zero net current), and the positive ion density is uniform and constant in time. The electrons are modeled as N sheets having charge-to-mass ratio -e/m that move in one dimension (along x) under the action of the time-varying fields produced by all the other sheets, the fixed ion charge density, and the charges on the walls. Electrons do not collide with other electrons, ions, or neutrals in this simulation.

M.A. Lieberman and A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, 2nd ed. (John Wiley, New York, 2005).

Introduction

Sheath?

Four thousand sheets were used with $T_e = 1V$ and $n_i = n_e = 10^{13}\ m^{-3}$ at time t = 0. In (a), (b), (c), and (d), we, respectively, see the v_x–x electron phase space, electron density, electric field, and potential after the sheath has formed, at t = 0.77 μs. The time history of *N* is shown in (e); 40 sheets have been lost to form the sheaths. Figures 1.11a–d show the absence of electrons near each wall over a sheath width $s \approx 6$ mm. Except for fluctuations due to the finite *N*, the field in the bulk plasma is near zero, and the fields in the sheaths are large and point from the plasma to the walls. (E_x is negative at the left wall and positive at the right wall to repel plasma electrons.)

M.A. Lieberman and A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, 2nd ed. (John Wiley, New York, 2005).

Introduction

Sheath?

The potential in the center of the discharge is $V_p \approx 2.5V$ and falls to zero at the left wall (this wall is grounded by definition). The potential at the right wall is also low, but we see in (*f*) that it oscillates in time. We will see in Chapter 4 that these are *plasma oscillations*. We would not see them if the initial sheet positions and velocities were chosen exactly symmetrically about the midplane, or if many more sheets were used in the simulation. If the ions were also modeled as moving sheets, then on a longer timescale we would see ion acceleration within the sheaths, and a consequent drop in ion density near the walls, as sketched in Figure 1.10b. We return to this in Chapter 6.

M.A. Lieberman and A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, 2nd ed. (John Wiley, New York, 2005).

Introduction

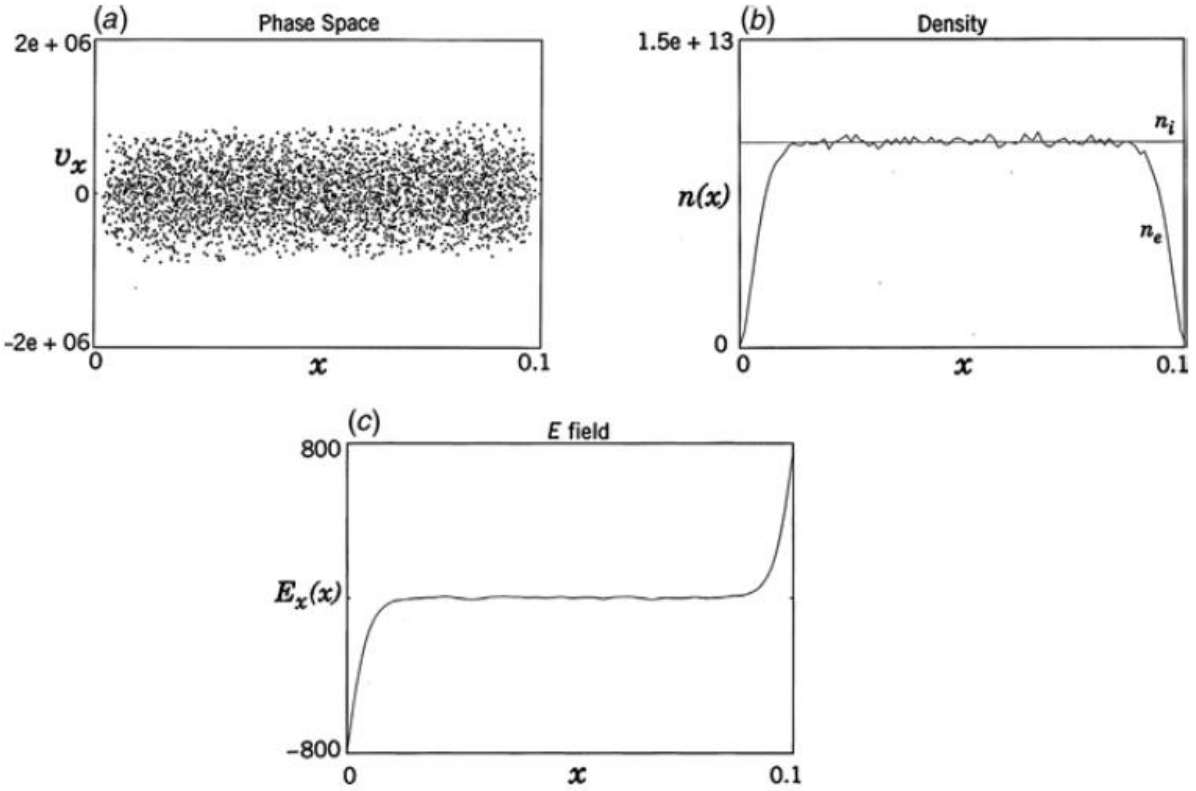


FIGURE 1.11. PIC simulation of positive ion sheath formation: (*a*) v_x–x electron phase space, with horizontal scale in meters; (*b*) electron density n_e; (*c*) electric field E_x; (*d*) potential Φ; (*e*) electron number $\mathcal{N}$ versus time t in seconds; (*f*) right hand potential V_r versus time t.

M.A. Lieberman and A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, 2nd ed. (John Wiley, New York, 2005).

Introduction

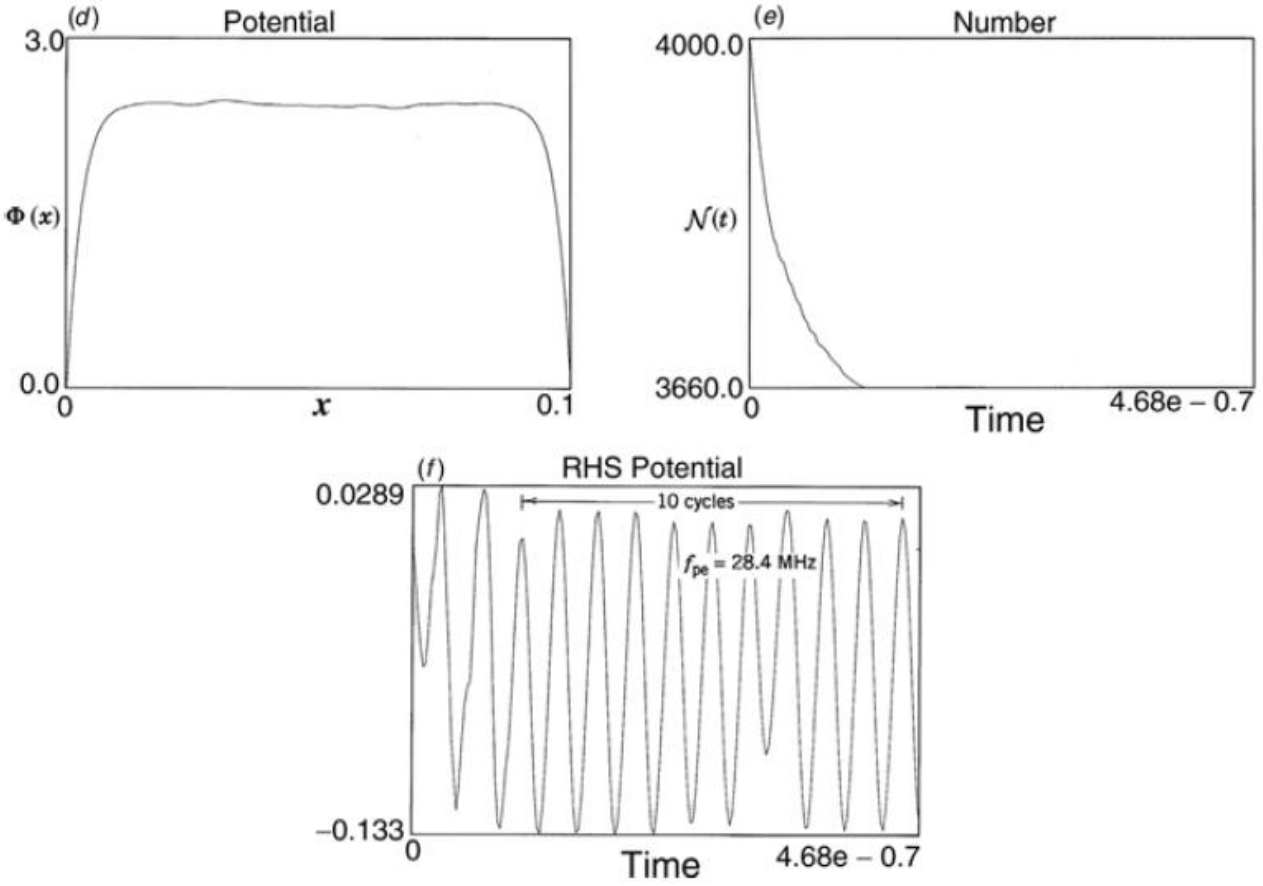


FIGURE 1.11. (*Continued*).

M.A. Lieberman and A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, 2nd ed. (John Wiley, New York, 2005).

Introduction

Sheath?

The separation of discharges into bulk plasma and sheath regions is an important paradigm that applies to all discharges. The bulk region is quasi-neutral, and both instantaneous and time-averaged fields are low. The bulk plasma dynamics are described by diffusive ion loss at high pressures and by free-fall ion loss at low pressures. In the positive space charge sheaths, high fields exist, leading to dynamics that are described by various ion space charge sheath laws, including low-voltage sheaths and various high-voltage sheath models, such as collisionless and collisional Child laws and their modifications.

M.A. Lieberman and A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, 2nd ed. (John Wiley, New York, 2005).

Introduction

Sheath?

The plasma and sheath dynamics must be joined at their interface. As will be seen in Chapter 6, the usual joining condition is to require that the mean ion velocity at the plasma-sheath edge be equal to the ion sound (Bohm) velocity: $u_B = (eT_e/M)^{1/2}$, where e and M are the charge and mass of the ion, respectively, and Te is the electron temperature in volts.

M.A. Lieberman and A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, 2nd ed. (John Wiley, New York, 2005).

Introduction

DISCHARGES

Radio Frequency Diodes

Capacitively driven radio frequency (rf) discharges—so-called rf diodes—are commonly used for materials processing. An idealized discharge in plane parallel geometry, shown in Figure 1.12a, consists of a vacuum chamber containing two planar electrodes separated by a spacing l and driven by an rf power source. The substrates are placed on one electrode, feedstock gases are admitted to flow through the discharge, and effluent gases are removed by the vacuum pump. Coaxial discharge geometries, such as the "hexode" shown in Figure 1.12b, are also in widespread use.

M.A. Lieberman and A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, 2nd ed. (John Wiley, New York, 2005).

Introduction

Discharges

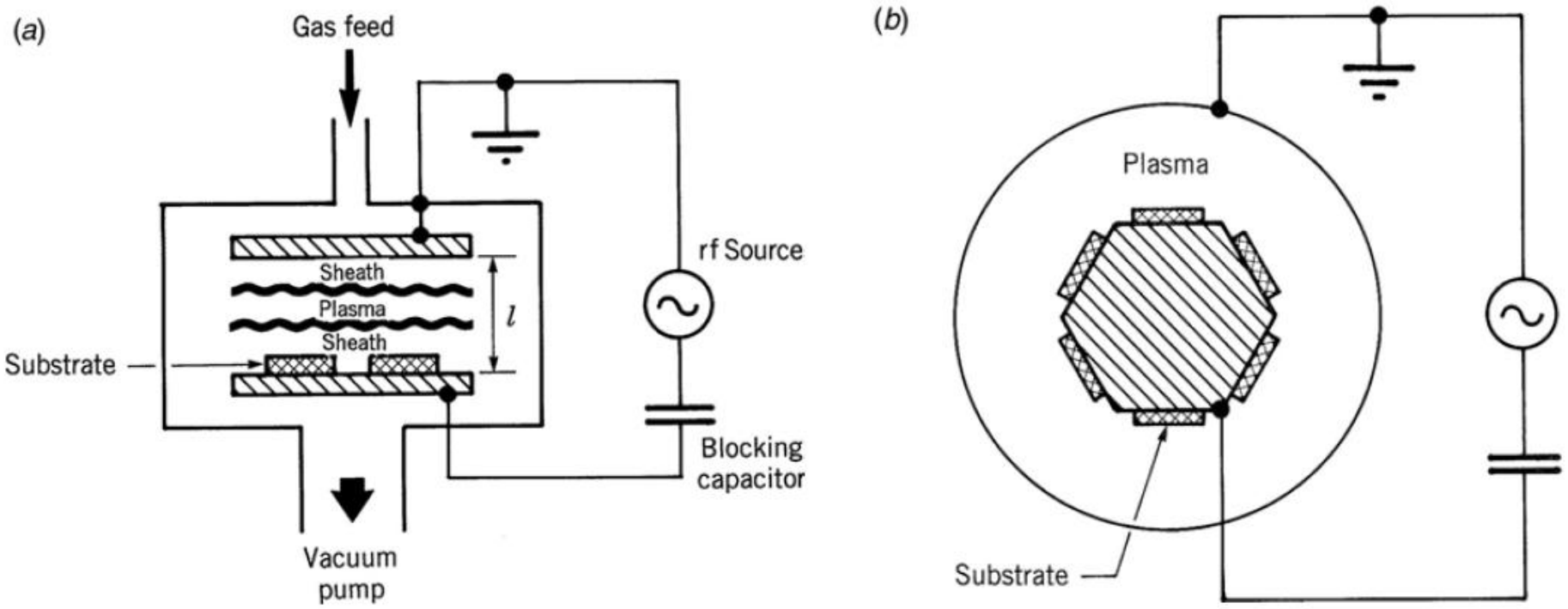


FIGURE 1.12. Capacitive rf discharges in (*a*) plane parallel geometry and (*b*) coaxial "hexode" geometry (after Lieberman and Gottscho, 1994).

M.A. Lieberman and A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, 2nd ed. (John Wiley, New York, 2005).

DISCHARGES

Radio Frequency Diodes

Typical parameters are shown in Table 1.1. The typical rf driving voltage is V_{rf} = 100–1000 V, and the plate separation is l = 2–10 cm. When operated at low pressure, with the wafer mounted on the powered electrode, and used to remove substrate material, such reactors are commonly called reactive ion etchers (RIEs)—a misnomer, since the etching is a chemical process enhanced by energetic ion bombardment of the substrate, rather than a removal process due to reactive ions alone.

M.A. Lieberman and A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, 2nd ed. (John Wiley, New York, 2005).

Introduction

Discharges

TABLE 1.1. Range of Parameters for rf Diode and High-Density Discharges

Parameter	rf Diode	High-Density Source
Pressure p (mTorr)	10–1000	0.5–50
Power P (W)	50–2000	100–5000
Frequency f (MHz)	0.05–13.56	0–2450
Volume $\mathcal{V}$ (L)	1–10	2–50
Cross-sectional area A (cm^2)	300–2000	300–500
Magnetic field B (kG)	0	0–1
Plasma density n (cm^{-3})	10^9–10^{11}	10^{10}–10^{12}
Electron temperature T_e (V)	1–5	2–7
Ion acceleration energy $\mathcal{E}_i$ (V)	200–1000	20–500
Fractional ionization x_{iz}	10^{-6}–10^{-3}	10^{-4}–10^{-1}

M.A. Lieberman and A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, 2nd ed. (John Wiley, New York, 2005).

Introduction

DISCHARGES

Radio Frequency Diodes

For anisotropic etching, typically pressures are in the range 10–100 mTorr, power densities are 0.1–1 W/cm^2, the driving frequency is 13.56 MHz, and multiple wafer systems are common. Typical plasma densities are relatively low, 10^9–10^{11} cm^{-3}, and the electron temperature is of order 3 V. Ion acceleration energies (sheath voltages) are high, greater than 200 V, and fractional ionization is low.

M.A. Lieberman and A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, 2nd ed. (John Wiley, New York, 2005).

Introduction

DISCHARGES

Radio Frequency Diodes

The degree of dissociation of the molecules into reactive species is seldom measured but can range widely from less than 0.1 percent to nearly 100 percent depending on gas composition and plasma conditions. For deposition and isotropic etch applications, pressures tend to be higher, ion bombarding energies are lower, and frequencies can be lower than the commonly used standard of 13.56 MHz.

M.A. Lieberman and A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, 2nd ed. (John Wiley, New York, 2005).

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DISCHARGES

Radio Frequency Diodes

The operation of capacitively driven discharges is reasonably well understood. As shown in Figure 1.13 for a symmetrically driven discharge, the mobile plasma electrons, responding to the instantaneous electric fields produced by the rf driving voltage, oscillate back and forth within the positive space charge cloud of the ions. The massive ions respond only to the time-averaged electric fields. Oscillation of the electron cloud creates sheath regions near each electrode that contain net positive charge when averaged over an oscillation period; that is, the positive charge exceeds the negative charge in the system, with the excess appearing within the sheaths.

M.A. Lieberman and A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, 2nd ed. (John Wiley, New York, 2005).

DISCHARGES

Radio Frequency Diodes

This excess produces a strong time-averaged electric field within each sheath directed from the plasma to the electrode. Ions flowing out of the bulk plasma near the center of the discharge can be accelerated by the sheath fields to high energies as they flow to the substrate, leading to energetic-ion enhanced processes. Typical ion-bombarding energies E_i can be as high as $V_{rf}/2$ for symmetric systems (Fig. 1.12) and as high as V_{rf} at the powered electrode for asymmetric systems (Fig. 1.13). A quantitative description of capacitive discharges is given in Chapter 11.

M.A. Lieberman and A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, 2nd ed. (John Wiley, New York, 2005).

Introduction

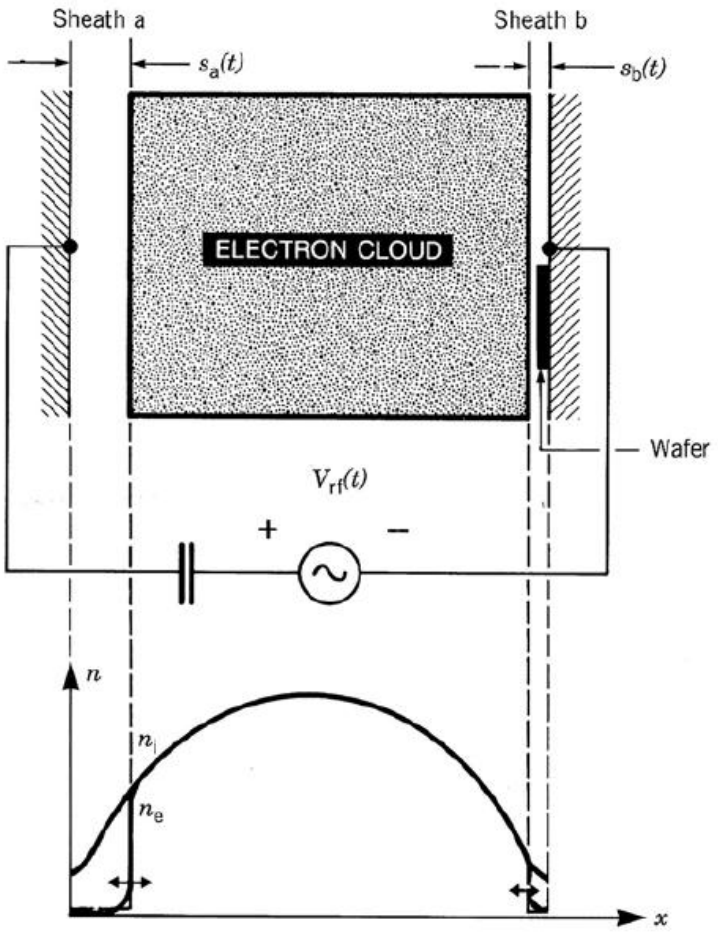


FIGURE 1.13. The physical model of an rf diode (after Lieberman and Gottscho, 1994).

M.A. Lieberman and A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, 2nd ed. (John Wiley, New York, 2005).

Introduction

DISCHARGES

Radio Frequency Diodes

We note that the positive ions continuously bombard the electrode over an rf cycle. In contrast, electrons are lost to the electrode only when the oscillating cloud closely approaches the electrode. During that time, the instantaneous sheath potential collapses to near zero, allowing sufficient electrons to escape to balance the ion charge delivered to the electrode. Except for such brief moments, the instantaneous potential of the discharge must always be positive with respect to any large electrode and wall surface; otherwise the mobile electrons would quickly leak out. Electron confinement is ensured by the presence of positive space charge sheaths near all surfaces.

M.A. Lieberman and A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, 2nd ed. (John Wiley, New York, 2005).

Introduction

DISCHARGES

Radio Frequency Diodes

We will see that a crucial limiting feature of rf diodes is that the ion-bombarding flux $\Gamma_i = nu_B$ and bombarding energy E_i cannot be varied independently. The situation is analogous to the lack of independent voltage and current control in diode vacuum tubes or semiconductor pn junctions. For a reasonable (but relatively low) ion flux, as well as a reasonable dissociation of the feedstock gas, sheath voltages at the driven electrode are high. For wafers placed on the driven electrode, this can result in undesirable damage, or loss of linewidth control. Furthermore, the combination of low ion flux and high ion energy leads to a relatively narrow process window for many applications.

M.A. Lieberman and A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, 2nd ed. (John Wiley, New York, 2005).

Introduction

DISCHARGES

Radio Frequency Diodes

The low process rates resulting from the limited ion flux in rf diodes often mandates multiwafer or batch processing, with consequent loss of wafer-to-wafer reproducibility. Higher ion and neutral fluxes are generally required for single-wafer processing in a clustered tool environment, in which a single wafer is moved by a robot through a series of process chambers. Clustered tools are used to control interface quality and are said to have the potential for significant cost savings in fabricating ICs. Finally, low fractional ionization poses a significant problem for processes where the feedstock costs and disposal of effluents are issues.

M.A. Lieberman and A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, 2nd ed. (John Wiley, New York, 2005).



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DISCHARGES

Radio Frequency Diodes

To meet the linewidth, selectivity, and damage control demands for next generation fabrication, the mean ion bombarding energy, and its energy distribution, should be controllable independently of the ion and neutral fluxes. Some control over ion-bombarding energy can be achieved by putting the wafer on the undriven electrode and independently biasing this electrode with a second rf source. Although these so-called rf triode systems are in use, processing rates are still low at low pressures and sputtering contamination is an issue.

M.A. Lieberman and A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, 2nd ed. (John Wiley, New York, 2005).

Introduction

DISCHARGES

Radio Frequency Diodes

Another approach is dual frequency operation, in which a high- and a low-frequency rf source are used to drive one or both plates of an rf diode. The high frequency mainly controls the ion flux and the low frequency controls the ion bombarding energy. Using a frequency higher than the conventional frequency of 13.56 MHz for the high-frequency drive results in an increased ion flux to the substrate for a fixed power input and allows the low-frequency drive to better control the ion energy. High frequencies of 27.1, 60, or 160 MHz, and low frequencies of 2 or 13.56 MHz, are used commercially.

M.A. Lieberman and A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, 2nd ed. (John Wiley, New York, 2005).

Introduction

DISCHARGES

Radio Frequency Diodes

Various magnetically enhanced rf diodes and triodes have also been developed to improve performance of the rf reactor. These include, for example, magnetically enhanced reactive ion etchers (MERIEs), in which a direct current (dc) magnetic field of 50–300 G is applied parallel to the powered electrode, on which the wafer sits. The magnetic field increases the efficiency of power transfer from the source to the plasma and also enhances plasma confinement. This results in a reduced sheath voltage and an increased plasma density when the magnetic field is applied.

M.A. Lieberman and A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, 2nd ed. (John Wiley, New York, 2005).

Introduction

DISCHARGES

Radio Frequency Diodes

However, the plasma generated is strongly nonuniform both radially and azimuthally. To increase process uniformity (at least azimuthally), the magnetic field is slowly rotated in the plane of the wafer, for example, at a frequency of 0.5 Hz. While this is an improvement, MERIE systems may not have good uniformity, which may limit their applicability to next-generation, submicrometer device fabrication.

M.A. Lieberman and A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, 2nd ed. (John Wiley, New York, 2005).



Introduction

DISCHARGES

High-Density Sources

The limitations of rf diodes and their magnetically enhanced variants have led to the development of a new generation of low-pressure, high-density plasma sources. A few examples are shown schematically in Figure 1.14, and typical source and plasma parameters are given in Table 1.1. A quantitative description is given in Chapters 12 and 13. In addition to high density and low pressure, a common feature is that the rf or microwave power is coupled to the plasma across a dielectric window, rather than by direct connection to an electrode in the plasma, as for an rf diode.

M.A. Lieberman and A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, 2nd ed. (John Wiley, New York, 2005).

DISCHARGES

High-Density Sources

This noncapacitive power transfer is the key to achieving low voltages across all plasma sheaths at electrode and wall surfaces. Direct current (dc) voltages, and hence ion acceleration energies, are then typically 20–30 V at all surfaces. To control the ion energy, the electrode on which the wafer is placed can be independently driven by a capacitively coupled rf source. Hence independent control of the ion/radical fluxes (through the source power) and the ion-bombarding energy (through the wafer electrode power) is possible.

M.A. Lieberman and A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, 2nd ed. (John Wiley, New York, 2005).

DISCHARGES

High-Density Sources

The common features of power transfer across dielectric windows and separate bias supply at the wafer electrode are illustrated in Figure 1.14. However, sources differ significantly in the means by which power is coupled to the plasma. For the electron cyclotron resonance (ECR) source shown in Figure 1.14a, one or more electromagnet coils surrounding the cylindrical source chamber generate an axially varying dc magnetic field.

M.A. Lieberman and A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, 2nd ed. (John Wiley, New York, 2005).

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High-Density Sources

Microwave power is injected axially through a dielectric window into the source plasma, where it excites a right-hand circularly polarized wave that propagates to a resonance zone, for cold electrons at $\omega = \omega_{ce}$, where the wave is absorbed. Here $\omega = 2\pi f$ is the applied radian frequency and $\omega_{ce} = eB/m$ is the electron gyration frequency at resonance. For the typical microwave frequency used, f = 2450 MHz, the resonant magnetic field is $B \approx 875$ G. The plasma streams out of the source into the process chamber in which the wafer is located.

M.A. Lieberman and A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, 2nd ed. (John Wiley, New York, 2005).

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High-Density Sources

A helicon source is shown in Figure 1.14b. A weak (50–200 G) dc axial magnetic field together with an rf-driven antenna placed around the dielectric cylinder that forms the source chamber allows excitation of a helicon wave within the source plasma. Resonant wave–particle interaction is believed to transfer the wave energy to the plasma. For the helical resonator source shown in Figure 1.14c, the external helix and conducting cylinder surrounding the dielectric discharge chamber form a slow wave structure, that is, supporting an electromagnetic wave with phase velocity much less than the velocity of light.

M.A. Lieberman and A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, 2nd ed. (John Wiley, New York, 2005).

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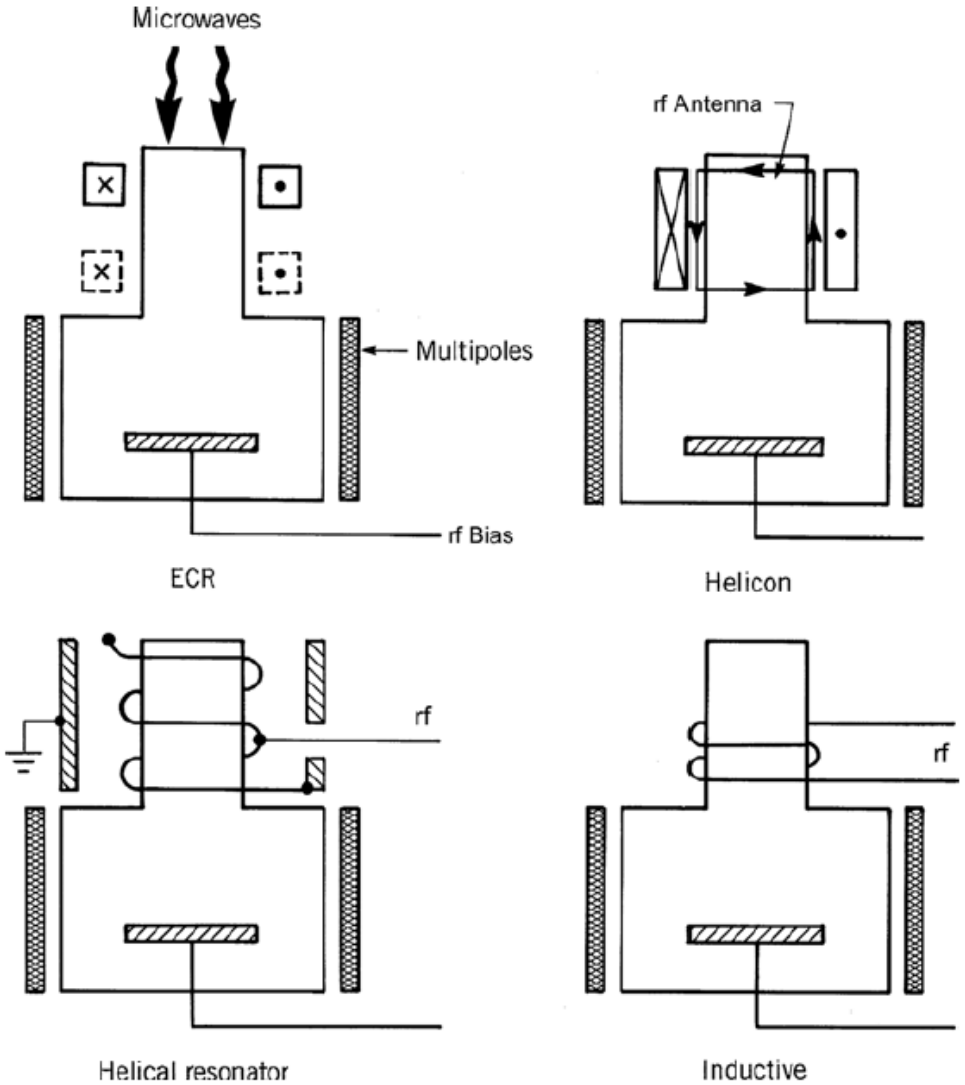


FIGURE 1.14. Some high-density "remote" sources (after Lieberman and Gottscho, 1994).



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Efficient coupling of the rf power to the plasma is achieved by excitation of a resonant axial mode. An inductive (or transformer) coupled source is shown in Figure 1.14d. Here the plasma acts as a single-turn, lossy conductor that is coupled to a multiturn nonresonant rf coil across the dielectric discharge chamber; rf power is inductively coupled to the plasma by transformer action. In contrast to ECR and helicon sources, a dc magnetic field is not required for efficient power coupling in helical resonator or inductive sources.

M.A. Lieberman and A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, 2nd ed. (John Wiley, New York, 2005).

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Figure 1.14 also illustrates the use of high-density sources to feed plasma into a relatively distinct, separate process chamber in which the wafer is located. As shown in the figure, the process chamber can be surrounded by dc multipole magnetic fields to enhance plasma confinement near the process chamber surfaces, while providing a magnetic near-field-free plasma environment at the wafer. Such configurations are often called "remote" sources, a misnomer since at low pressures considerable plasma and free radical production occurs within the process chamber near the wafer.

M.A. Lieberman and A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, 2nd ed. (John Wiley, New York, 2005).

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High-Density Sources

Sometimes, the source and process chambers are more integral, for example, the wafer is placed very near to the source exit, to obtain increased ion and radical fluxes, reduced spread in ion energy, and improved process uniformity. But the wafer is then exposed to higher levels of damaging radiation.

M.A. Lieberman and A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, 2nd ed. (John Wiley, New York, 2005).

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High-Density Sources

Although the need for low pressures, high fluxes, and controllable ion energies has motivated high-density source development, there are many issues that need to be resolved. A critical issue is achieving the required process uniformity over 300-mm wafer diameters. In contrast to the nearly one-dimensional geometry of typical rf diodes (two closely spaced parallel electrodes), high-density cylindrical sources can have length-to-diameter ratios of order or exceeding unity. Plasma formation and transport in such geometries are inherently radially nonuniform.

M.A. Lieberman and A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, 2nd ed. (John Wiley, New York, 2005).

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Another critical issue is efficient power transfer (coupling) across dielectric windows over a wide operating range of plasma parameters. Degradation of and deposition on the window can also lead to irreproducible source behavior and the need for frequent, costly cleaning cycles. Low-pressure operation leads to severe pumping requirements for high deposition or etching rates and hence to the need for large, expensive vacuum pumps.

M.A. Lieberman and A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, 2nd ed. (John Wiley, New York, 2005).

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Furthermore, plasma and radical concentrations become strongly sensitive to reactor surface conditions, leading to problems of reactor aging and process irreproducibility. Finally, dc magnetic fields are required for some source concepts. These can lead to magnetic field-induced process nonuniformities and damage, as seen, for example, in MERIE systems.

M.A. Lieberman and A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, 2nd ed. (John Wiley, New York, 2005).

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Figure 1.15 illustrates schematically the central problem of discharge analysis, using the example of an rf diode. Given the control parameters for the power source (frequency ω, driving voltage V_{rf} , or absorbed power P_{abs}), the feedstock gas (pressure p, flow rate, and chemical composition), and the geometry (simplified here to the discharge length *l*), then find the plasma parameters, including the plasma density n_i, the etchant density n_F, the ion and etchant fluxes Γ_i and Γ_F hitting the substrate, the electron and ion temperatures T_e and T_i, the ion bombarding energy E_i, and the sheath thickness *s*. The control parameters are the "knobs" that can be "turned" in order to "tune" the properties of the discharge.

M.A. Lieberman and A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, 2nd ed. (John Wiley, New York, 2005).

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The tuning range for a given discharge is generally limited. Sometimes one type of discharge will not do the job no matter how it is tuned, so another type must be selected. As suggested in Figures 1.12 and 1.14, a bewildering variety of discharges are used for processing. Some are driven by rf, some by dc, and some by microwave power sources. Some use magnetic fields to increase the plasma confinement or the efficiency of power absorption. One purpose of this book is to guide the reader toward making wise choices when designing discharges used for processing.

M.A. Lieberman and A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, 2nd ed. (John Wiley, New York, 2005).

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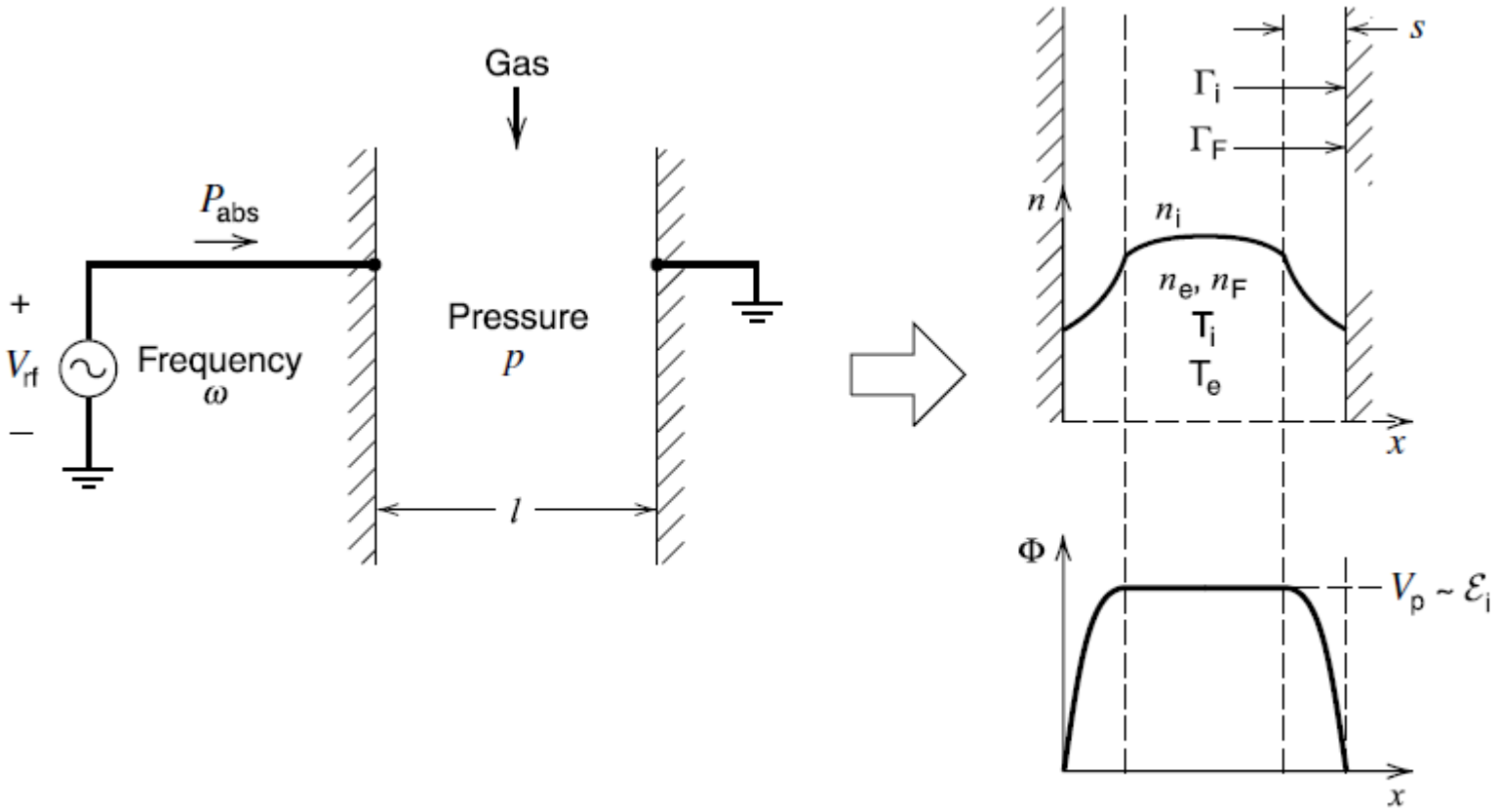


FIGURE 1.15. The central problem of discharge analysis.

Introduction

Symbols and units

Prof. ChinWook Chung's Lecture Notes on "Material Processing of Semiconductors".

- $e = 1.6 \times 10^{-19}$ C
- U(joules) = $e\varepsilon$(V)
- 1 Torr ≈ 133.3Pa,1 Pa=7.5 mTorr
- 1 atm ~ 1.013×10^5 Pa = 760 Torr
- 1 (Tesla) = 10^4 G
- eT (V)=kT (K), 1eV=1.6×10^{-19}J
- T = 297K → 0.026eV
- 1eV → T = 11,600 K