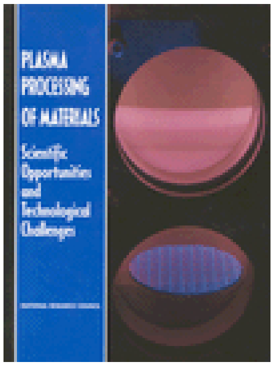

Plasma Processing of Materials: Scientific Opportunities and Technological Challenges

Panel on Plasma Processing of Materials, Plasma Science Committee, Board on Physics and Astonomy, National Research Council

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Panel on Plasma Processing of Materials
Plasma Science Committee
Board on Physics and Astronomy
Commission on Physical Sciences, Mathematics, and Applications
National Research Council

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Washington, D.C. 1991

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Preface

In 1989, the Executive Committee of the Division of Plasma Physics (DPP) of the American Physical Society (APS) made a presentation to the Board on Physics and Astronomy (BPA) arguing that a Plasma Science Committee should be established by the National Research Council (NRC). Shortly thereafter, the new committee was formed under the auspices of the BPA.

Among its first projects, the Plasma Science Committee (PLSC) launched a study of plasma processing of materials by convening an informational meeting at which representatives of the materials processing community provided technical background and identified issues and priorities. It was noted that low-temperature plasma science is vitally important to the industrial sector in areas such as materials processing and semiconductor fabrication. Yet the basic research and education efforts in this area are inadequate and are not nearly commensurate with its technical and economic importance. Accordingly, the PLSC called for the formation of a panel of specialists to carry out a science and technology assessment with the following specific charge:

- Evaluate the potential impact of advances in low-temperature plasma science on surface processing technology, with emphasis on semiconductor applications.
- Identify key research problems in plasma physics and chemistry and the interaction of plasmas with surfaces.
- Recommend means to bring to bear the strengths of the plasma science community on the scientific, technological, and educational issues identified in the study.

The Panel on Plasma Processing of Materials (PPPM) was organized in 1990 and met several times to address this charge. The panel was selected to provide representation from industry as well as from academic institutions, and liaison members were appointed who concurrently served on the Plasma Science Committee, the Solid State Sciences Committee (SSSC), and the Committee on Atomic, Molecular, and Optical Sciences (CAMOS).

A daunting problem for the panel stemmed from the diversity of industrial applications of plasma-based systems used in the processing of materials. In its deliberations and its effort to focus the study, the panel concerned itself with two major areas of industrial applications, namely, microelectronics and aerospace. Three subpanels were formed to assess (1) applications of plasma processing of materials in the electronics and aerospace industries, (2) the basic plasma science that supports the applications, and (3) the related educational needs. The subpanels were charged to confront issues affecting the future health of the technology and science, the competitive position of the U.S. technology, identification of emerging technologies, the role of funding and coordination of research goals, and cooperation among industrial, academic, and national laboratory resources.

A two-day workshop was held early in 1991 to bring together some two dozen additional experts from the low-temperature plasma community for the purpose of soliciting their review of the panel's draft findings and to obtain additional input. Workshop participants reviewed a preliminary report by the panel and followed the topical approach of the subpanels. The workshop presentations and breakout groups emphasized identification of issues. The acknowledged diversity of subject matter was indeed matched by the diverse views of the participants, which led to lively debate but also to consensus on many of the key issues. This report, prepared by the Panel on Plasma Processing of Materials, is intended to summarize the views of the working panel members, the input received as a result of the workshop, the useful comments of numerous colleagues contacted by the panel, and many helpful suggestions contributed by the report's NRC-appointed peer reviewers.

The Panel on Plasma Processing of Materials finds that plasma processing of materials is a technology critical to implementing some of the key recommendations of the NRC study *Materials Science and Engineering for the 1990s* (National Academy Press, Washington, D.C., 1989) and to enhancing the health of the technologies identified in *the Report of the National Critical Technologies Panel* (U.S. Government Printing Office, Washington, D.C., 1991), specifically in the areas of materials synthesis and processing and microelectronic processing.

Although the work of the panel is now complete, it is the hope of its members that this report will clarify the critical importance of low-energy plasma science in materials processing and that a coordinated national focus will be developed to meet the demanding technological challenges that lie ahead. The diversity and emerging nature of plasma processing suggest that this will not be an easy task, but it is one that must not fail, given the economic importance of the technology and its enormous potential for stimulating economic growth.

Acknowledgments

The panel is grateful to R. McGrath for his extensive contributions to the chapter on education in plasma science, to J. Verdeyen for his input on the history of low-energy plasma science, and to R. Matula for his extensive literature searches. It is also indebted to J. Fincke and D. E. Ibbotson for their contributions to the basic science section, to A. Kornblit for his contribution to the applications section, and to J. T. Herron for his work on chemical kinetics and data base requirements. Contributions from E. S. Aydil, K. Ceraso, D. Economou, D. B. Graves, C. Jurgensen, L. E. Katz, S. Marshall, J.P. McVittie, G. Oehrlein, K. Olasupo, G. S. Selwyn, and D. Vitkavage are gratefully acknowledged. The panel could not have completed its work without the help of its NRC staff officer, Ronald D. Taylor. Thanks are also due to the editor, Susan Maurizi, and Anne Simmons, who prepared the manuscript.

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1

Summary, Findings, Conclusions, And Recommendations

SUMMARY

This study focuses on the plasma processing of materials, a technology that impacts and is of vital importance to several of the largest manufacturing industries in the world. Foremost among these industries is the electronics industry, in which plasma-based processes are indispensable for the manufacture of very large-scale integrated (VLSI) microelectronic circuits (or chips). Plasma processing of materials is also a critical technology in the aerospace, automotive, steel, biomedical, and toxic waste management industries. Because plasma processing is an integral part of the infrastructure of so many American industries, it is important for both the economy and the national security that America maintain a strong leadership role in this technology.

A plasma is a partially or fully ionized gas containing electrons, ions, and neutral atoms or molecules. In Chapter 2, the panel categorizes different kinds of plasmas and focuses on properties of man-made low-energy, highly collisional plasmas that are particularly useful in materials processing applications. The outstanding properties of most plasmas applied to processing of materials are associated with nonequilibrium conditions. These properties present a challenge to the plasma scientist and an opportunity to the technologist. The opportunities for materials processing stem from the ability of a plasma to provide a highly excited medium that has no chemical or physical counterpart in a natural, equilibrium environment. Plasmas alter the normal pathways through which chemical systems evolve from one stable state to another, thus providing the potential to produce materials with properties that are not attainable by any other means.

Applications of plasma-based systems used to process materials are diverse because of the broad range of plasma conditions, geometries, and excitation methods that may be used. The scientific underpinnings of plasma applications are multidisciplinary and include elements of electrodynamics, atomic science, surface science, computer science, and industrial process control. Because of the diversity of applications and the multidisciplinary nature of the science, scientific understanding lags technology. This report highlights this critical issue.

A summary of the many industrial applications of plasma-based systems for processing materials is included in Chapter 2. Electronics and aerospace are the two major industries that are served by plasma processing technologies, although the automotive industry is likely to become a significant user of plasma-processed materials like those now in widespread use in the aerospace industry. The critical role of plasma processing technology in industry is illustrated in Chapter 2.

For the electronics industry more than for any other considered by the panel, the impact of—and the critical and urgent need for—plasma-based materials processing is overwhelming. Thus Chapter 3 further elucidates plasma processing of electronic materials and, in particular, the use of plasmas in fabricating microelectronic components. The plasma equipment industry is an integral part of the electronics industry and has experienced dramatic growth in recent years because of the increasing use of plasma processes to meet the demands of fabricating devices with continually shrinking dimensions. In this country, the plasma equipment industry is composed of many small companies loosely connected to integrated circuit manufacturers. In Japan, on the other hand, equipment vendors and device manufacturers are tightly linked and are often parts of the same company.

Plasma processes used today in fabricating microelectronic devices have been developed largely by time-consuming, costly, empirical exploration. The chemical and physical complexity of plasma-surface interactions has so far eluded the accurate numerical simulation that would enable process design. Similarly, plasma reactors have also been developed by trial and error. This is due, in part, to the fact that reactor design is intimately intertwined with the materials process for which it will be used. Nonetheless, fundamental studies of surface processes and plasma phenomena—both experimental and numerical—have contributed to process development by providing key insights that enable limitation of the broad process-variable operating space. The state of the science that underpins plasma processing technology in the United States is outlined in Chapter 4. Although an impressive arsenal of both experimental and numerical tools has been developed, significant gaps in understanding and lack of instrumentation limit progress.

The broad interdisciplinary nature of plasma processing is highlighted in the discussion of education issues outlined in Chapter 5, which addresses the challenges and opportunities associated with providing a science education in the area of plasma processing. For example, graduate programs specifically focused on plasma processing are rare because of insufficient funding of university research programs in this field. By contrast, both Japan and France have national initiatives that support education and research in plasma processing.

FINDINGS, CONCLUSIONS, AND RECOMMENDATIONS

Finding and Conclusion: In recent years, the number of applications requiring plasmas in the processing of materials has increased dramatically. Plasma processing is now indispensable to the fabrication of electronic components and is widely used in the aerospace industry and other industries. However, the United States is seeing a serious decline in plasma reactor development that is critical to plasma processing steps in the manufacture of VLSI microelectronic circuits. In the interest of the U.S. economy and national defense, renewed support for low-energy plasma science is imperative.

Finding and Conclusion: The demand for technology development is outstripping scientific understanding of many low-energy plasma processes. The central scientific problem underlying plasma processing concerns the interaction of low-energy collisional plasmas with solid surfaces. Understanding this problem requires knowledge and expertise drawn from plasma physics, atomic physics, condensed matter physics, chemistry, chemical engineering, electrical engineering, materials science, computer science, and computer engineering. In the absence of a coordinated approach, the diversity of the applications and of the science tends to diffuse the focus of both.

Finding: Technically, U.S. laboratories have made many excellent contributions to plasma processing research—making fundamental discoveries, developing numerical algorithms, and inventing new diagnostic techniques. However, poor coordination and inefficient transfer of insights gained from this research have inhibited its use in the design of new plasma reactors and processes.

Finding: The Panel on Plasma Processing of Materials finds that plasma processing of materials is a critical technology that is necessary to implement key recommendations contained in the National Research Council report *Materials Science and Engineering for the 1990s* (National Academy Press, Washington, D.C., 1989) and to enhance the health of technologies as identified in *Report of the National Critical Technologies Panel* (U.S. Government Printing Office, Washington, D.C., 1991). Specifically, plasma processing is an essential element in the synthesis and processing arsenal for manufacturing electronic, photonic, ceramic, composite, high-performance metal, and alloy materials.

Accordingly, the panel recommends:

- **Plasma processing should be identified as a component program of the Federal Initiative on advanced materials synthesis and processing that currently is being developed by the Office of Science and Technology Policy.**
- **Through such a Plasma Processing Program, federal funds should be allocated specifically to stimulate focused research in plasma processing, both basic and applied, consistent with the long-term economic and defense goals of the nation.**
- **The Plasma Processing Program should not only provide focus on common goals and promote coordination of the research performed by the national laboratories, universities, and industrial laboratories, but also integrate plasma equipment suppliers into the program.**

Finding and Conclusion: Currently, computer-based modeling and plasma simulation are inadequate for developing plasma reactors. As a result, the detailed descriptions required to guide the transfer of processes from one reactor to another or to scale processes from a small to a large reactor are not available. Until we understand how geometry, electromagnetic design, and plasma-surface interactions affect material properties, the choice of plasma reactor for a given process will not be obvious, and costly trial-and-error methods will continue to be used. Yet there is no fundamental obstacle to improved modeling and simulation nor to the eventual creation of computer-aided design (CAD) tools for designing plasma reactors. The key missing ingredients are the following:

1. *A reliable and extensive plasma data base against which the accuracy of simulations of plasmas can be compared*. Plasma measurement technologies are sophisticated, but at present experiments are performed on a large variety of different reactors under widely varying conditions. A coordinated effort to diagnose simple, reference reactors is necessary to generate the necessary data base for evaluation of simulation results and to test new and old experimental methodology.
2. *A reliable and extensive input data base for calculating plasma generation, transport, and surface interaction*. The dearth of basic data needed for simulation of plasma generation, transport, and surface reaction processes results directly from insufficient generation of data, insufficient data compilation, insufficient distribution of data, and insufficient funding of these activities. The critical basic data needed for simulations and experiments have not been prioritized. For plasma-surface interactions, in particular, lack of data has precluded the formation of mechanistic models on which simulation tools are based. Further experimental studies are needed to elucidate these mechanisms.
3. *Efficient numerical algorithms and supercomputers for simulating magnetized plasmas in three dimensions*. The advent of unprecedented supercomputer capability in the next 5 to 10 years will have a major impact in this area, provided that current simulation methods are expanded to account for multidimensional effects in magnetized plasmas.

Accordingly, the panel recommends:

- **The Plasma Processing Program should include a thrust toward development of computer-aided design tools for developing and designing new plasma reactors.**
- **The Plasma Processing Program should emphasize a coordinated approach toward generating the diagnostic and basic data needed for improved plasma and plasma-surface simulation capability.**
- **A program to extend current algorithms for plasma reactor simulation should be included among the activities funded under the umbrella of the federal High**

Performance Computing and Communications program[1] developed by the Office of Science and Technology Policy and started in FY92.

Finding and Conclusion: In the coming decade, custom-designed and custom-manufactured chips, *i.e*., application-specific integrated circuits (ASICs), will gain an increasing fraction of the world market in microelectronic components. This market, in turn, will belong to the flexible manufacturer who uses a common set of processes and equipment to fabricate many different circuit designs. Such flexibility in processing will result only from real understanding of processes and reactors. On the other hand, plasma processes in use today have been developed using a combination of intuition, empiricism, and statistical optimization. Although it is unlikely that detailed, quantitative, first-principles-based simulation tools will be available for process design in the near future, design aids such as expert systems, which can be used to guide engineers in selecting initial conditions from which the final process is derived, could be developed if gaps in our fundamental understanding of plasma chemistry were filled.

Finding and Conclusion: Three areas are recognized by the panel as needing concerted, coordinated experimental and theoretical research: surface processes, plasma generation and transport, and plasma-surface interactions. For surface processes, studies using well-controlled reactive beams impinging on well-characterized surfaces are essential for enhancing our understanding and developing mechanistic models. For plasma generation and transport, chemical kinetic data and diagnostic data are needed to augment the basic plasma reactor CAD tool. For studying plasma-surface interactions, there is an urgent need for *in situ* analytical tools that provide information on surface composition, electronic structure, and material properties.

Finding and Conclusion: Breakthroughs in understanding the science will be paced by development of tools for the characterization of the systems. To meet the coming demands for flexible device manufacturing, plasma processes will have to be actively and precisely controlled. But today no diagnostic techniques exist that can be used unambiguously to determine material properties related to device yield. Moreover, the parametric models needed to relate diagnostic data to process variables are also lacking.

According, the panel recommends:

- **The Plasma Processing Program should be dedicated in part to the development of plasma process expert systems.**
- **A coordinated program should be supported to generate basic data and simulation of surface processes, plasma generation and transport, and plasma-surface interactions.**
- **A program should be supported that focuses on development of new instrumentation for real-time, *in situ* monitoring for control and analysis.**

Finding: Research resources in low-energy plasma science in the United States are eroding at an alarming rate. U.S. scientists trained in this area in the 1950s and early 1960s are retiring or are moving to other areas of science for which support is more forthcoming. When compared to those in Japan and France, the U.S. educational infrastructure in plasma processing lacks focus, coordination, and funding. As a result, the United States will not be prepared to maintain its leading market position in plasma processing, let alone capture more market share as the plasma process industry grows into the 21st century.

Finding: Graduate programs are not offering adequate educational opportunities in the science of weakly ionized, highly collisional plasmas. An informal survey by the panel indicated that only a few U.S. universities offer formal course work in this science and that there are

[1] *Grand Challenges: High Performance Computing and Communications* , the FY 1992 U.S. Research and Development Program, Supplement to the President's Fiscal Year 1992 Budget, 1991.

insufficient texts on collisional plasmas and plasma processing. These deficiencies are a direct result of low-level funding for graduate research in plasma processing and low-energy plasmas.

Finding and Conclusion: The most serious need in undergraduate education is adequate, modern teaching laboratories. Due to the largely empirical nature of many aspects of plasma processing, proper training in the traditional scientific method, as provided in laboratory classes, is a necessary component of undergraduate education. The Instrumentation and Laboratory Improvement Program sponsored by the National Science Foundation has been partly successful in fulfilling these needs, but it is not sufficient.

Finding and Conclusion: Research experiences for undergraduates made available through industrial cooperative programs or internships are essential for high-quality technical education. But teachers and professors themselves must first be educated in low-energy plasma science and plasma processing before they can be expected to educate students. Industrial-university links can also help to impart a much needed, longer-term view to industrial research efforts.

Accordingly, the panel recommends:

- **As part of the Plasma Processing Program, government and industry together should support cooperative programs specific to plasma processing with universities and national laboratories.**
- **A program should be established to provide industrial internships for teachers and professors in the area of plasma processing.**

2

Plasma Processing And Low-Energy Plasma Science

Plasma processing technologies are of vital importance to several of the largest manufacturing industries in the world. Foremost among these industries is the electronics industry, in which plasma-based processes are indispensable for the manufacture of very large-scale integrated microelectronic circuits. Plasma processing of materials is also a critical technology in, for example, the aerospace, automotive, steel, biomedical, and toxic waste management industries (Figure 2.1). Most recently, plasma processing technology has been utilized increasingly in the emerging technologies of diamond film and superconducting film growth. Because plasma processing is an integral part of the infrastructure of so many vital American industries, it is important for both the economy and the national security that America maintain a strong leadership role in this technology.

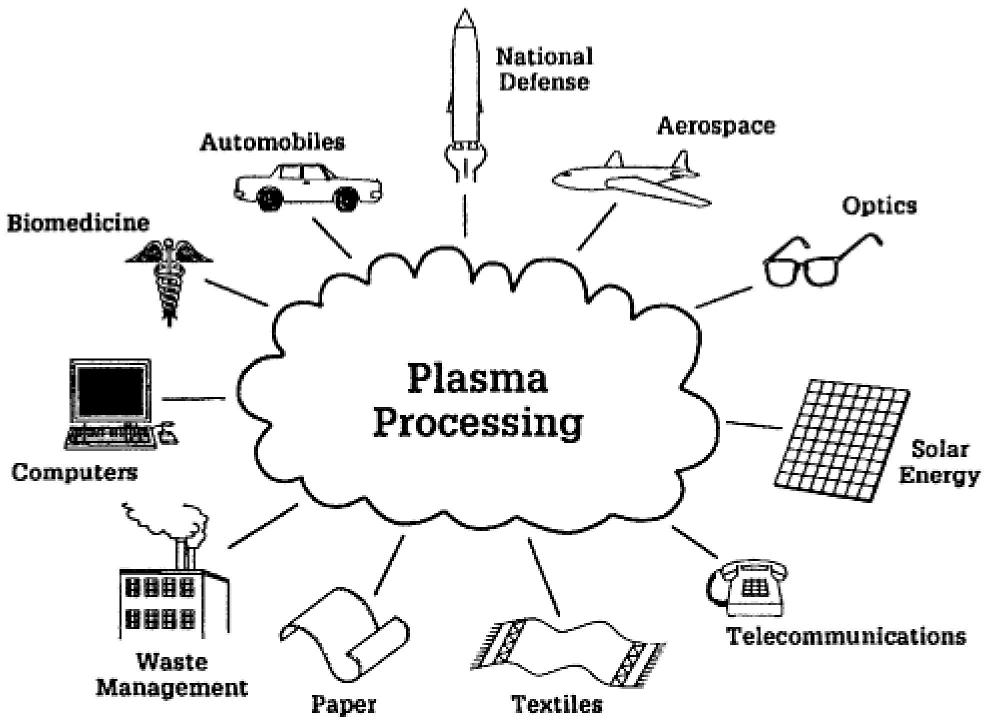

Figure 2.1
Plasma processing is a critical technology in many vital U.S. industries.

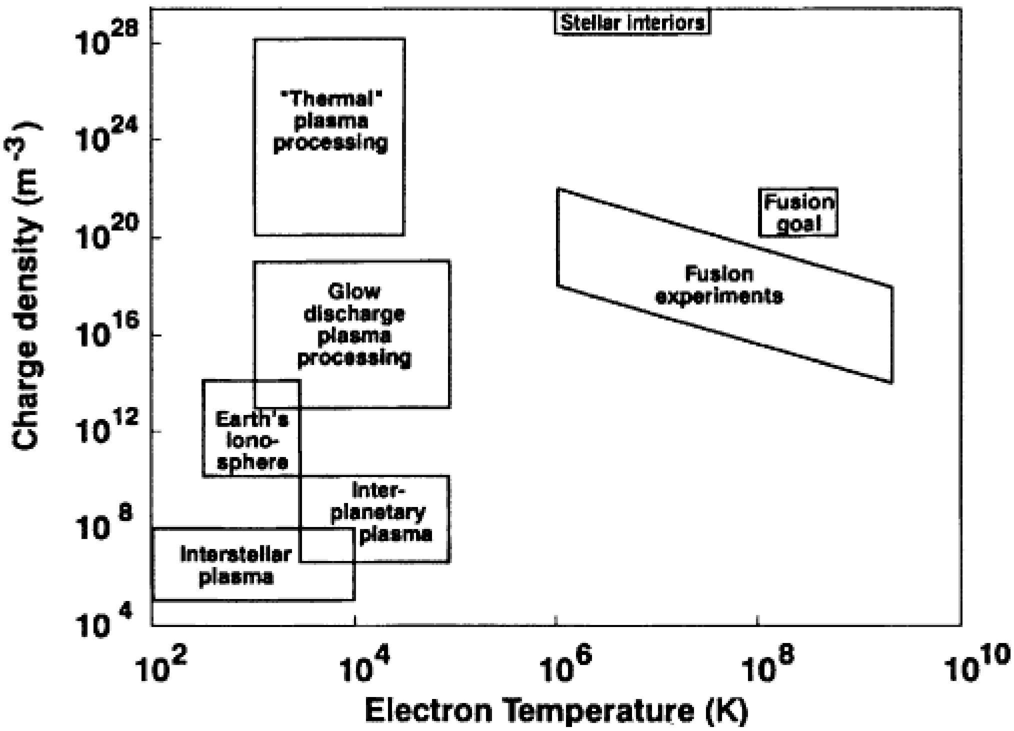

Figure 2.2
Classification of plasmas according to charge density per unit volume and electron temperature in degrees Kelvin. P lasmas used in materials processing cover a large portion of the low-energy density-temperature space.

CLASSIFICATION OF PLASMAS

A plasma is a partially or fully ionized gas containing electrons, ions, and neutral atoms and/or molecules. Plasma science is the study of the nonlinear collective interactions of electrically charged particles with each other, with neutral atoms and molecules, and with electric and magnetic fields. Figure 2.2 illustrates the wide range of electron densities and temperatures that are encountered in nature as well as in the laboratory.

Low-energy plasmas occupy a large portion of the density-temperature plane, with electron densities ranging from 10^5 to 10^{28} m^{-3} and electron temperatures ranging from 100 to 10^5 Kelvin. Two regimes in the density-temperature plane are characteristic of plasmas used in plasma processing. One of these includes glow discharges, in which the temperatures of electrons and heavy particles are widely disparate. The second includes thermal plasmas, in which electrons and heavy particles are in approximate thermal equilibrium. These plasmas are classical in nature in that the thermal kinetic energy is large in comparison to the average Coulomb interaction energy. Thus, charged particles usually interact weakly with each other, and electron collisions are usually most frequent with neutral atoms and molecules. The degree of ionization may range from a high percentage to less than 1 part per billion. These plasmas are governed by the laws of collective phenomena and atomic physics. Low-temperature plasmas, particularly glow plasmas, are not in thermal equilibrium and exhibit wide differences in electron, neutral, ion, vibrational, and rotational temperatures. Moreover, within each plasma species there are departures from equilibrium, and Maxwellian energy distributions are seldom observed. Steep gradients between the plasma and solid surfaces or between the plasma and cold gas introduce additional deviations from equilibrium and, in high-pressure plasmas, fluid and kinetic instabilities add to the complexity. Thus, for these conditions the terms *thermal* and *temperature* have no strict definition and are only used qualitatively. Because of the myriad interactions that can occur in the volume and at surfaces, the highly nonequilibrium character of these plasmas presents both challenges and opportunities in materials processing.

BRIEF HISTORY OF LOW-ENERGY PLASMA SCIENCE AND TECHNOLOGY

Although ionospheric and, indeed, many astrophysical plasmas are classified as low-energy plasmas, the bulk of plasma science that is currently practiced in this domain is gaseous electronics-based. in its original form, the gas discharge branch of Langmuir's plasma physics, founded in the early part of this century, focused on electron conduction and breakdown in gases, electron emission and other cathode phenomena, and excitation of atomic and molecular species by electron collisions. Applications of the physical principles derived in this new field of science developed rapidly, beginning with the carbon arc as a light source and followed by gas-discharge rectification, high-power switch gear, and welding arcs. The ubiquitous mercury arc lamp followed, as did the more sophisticated fluorescent discharge lamp.

These and related applications have drawn heavily on plasma science in their evolution since World War II and have enlarged the scope of the supporting science to include plasma chemistry, atomic and molecular physics, surface chemistry and physics, optics, high-temperature physics and chemistry, electrical engineering, and computer science. This new science supports many of the world's major industries and is an indispensable part of many military technologies.

- The use of plasma-based switch gear persists in the now huge power industry, while pulse power switches have been developed for use in high-power radars, discharge laser systems, and, indeed, in the switching of stored electrical power for high-energy plasma experimentation.
- The early work on discharge light sources has evolved as the core technology in the lighting industry. Here, the earlier carbon and mercury arcs have been supplanted with arcs containing sodium-mercury mixtures as well as rare-earth additives to improve color and efficiency.
- New lasing species including excimers have been discovered and exploited through the efforts of plasma science investigators, with the result that plasma-based, high-power lasers have formed a new and robust technology.
- Thermal plasmas have been used for materials processing for many years (see *Plasma Processing of Materials, National Academy Press*, Washington, D.C., 1985). A multimegawatt thermal plasma process has been used commercially for nitrogen fixation. Thermal plasmas for remelting of metals in arc furnaces and for welding are well known. Development of plasma spray processes has led to significant advances in coating technology, with the aerospace industry being the major beneficiary. Today, plasma spray technology is also used in the automotive industry, the medical implant industry, the petrochemical industry, the cutting tool industry, and the paper industry (see Figure 2.1). Thermal plasmas are widely used in metallurgical refining and waste-processing areas.
- The newest, and perhaps the largest, technology employing plasma science is the electronics industry(see Chapter 3). Low-pressure plasmas are vital in many plasma etching, deposition, and surface modification steps in the manufacture of nearly all integrated circuits.

- Beyond this, plasma-enhanced chemical vapor deposition (PECVD) and thermal plasma chemical vapor deposition (TPCVD) are used for high-rate vapor-phase preparation of diamond and superconducting films.

This pervasive use of plasmas in modern technology is a result of the range of parameters that can be accessed and that is inaccessible by any other means. No other medium can provide gas temperatures or energy densities as high as those of plasmas; no other medium can excite atomic and molecular species to radiate as efficiently; no other medium can be arranged to provide comparable transient and nonequilibrium conditions.

In materials processing, opportunity lies in the fact that a highly excited medium can be obtained with no chemical or physical counterpart accessible in the natural environment. Plasmas can thereby alter the normal pathways through which chemical systems evolve from one stable state to another and can thus enable production of novel materials.

The diversity of applications of plasma-based systems used to process materials is matched by the diversity of plasma conditions, geometries, and excitation methods. In just one segment of the applications, PECVD and etching, the gas pressures vary by more than 6 orders of magnitude, and the gas composition includes rare gases and complex molecules. The plasma excitation frequency spans the electromagnetic spectrum from direct current (dc) to microwave. The power loading of the gases ranges from milliwatts per cubic centimeter to tens of kilowatts per cubic centimeter. The substrates may be in direct contact with the plasma, biased relative to the plasma, or placed downstream from the plasma. The practitioners of this composite science must then call on a number of science resources, which include:

- Plasma electrodynamics and kinetics,
- Plasma and surface chemistry
- Basic data for cross sections and rates,
- Diagnostics of discharge and surface processes,
- Theory and predictive modeling, and
- Scaling and process control.

The scientific community has the challenging task of providing the multidisciplinary scientific underpinning that will enable responding to the strong technology pull that exists now and will grow in the future.

INDUSTRIAL APPLICATIONS OF PLASMA PROCESSING OF MATERIALS

The number of industrial applications of plasma-based systems for processing of materials and for surface modification is extensive, and many industries are impacted. Some of these processes and corresponding applications include:

- Plasma-controlled anisotropic etching in fabrication of microelectronic chips;
- Plasma deposition of silicon nitride for surface passivation and insulation;
- Surface oxidation used in fabrication of silicon-based microelectronic circuits;
- Plasma-enhanced chemical vapor deposition of amorphous silicon films used in solar cells;
- Plasma-surface treatment for improved film adhesion to polymer surfaces;
- Plasma nitriding, which is used to harden the surface of steel;
- Plasma-enhanced chemical vapor deposition and thermal plasma chemical vapor deposition of diamond thin films;
- Plasma spray deposition of ceramic or metal alloy coatings used for protection against wear or corrosion in aircraft and automotive engines;

- Plasma spray deposition of clearance control coatings;
- Plasma melting and refining of alloys;
- Plasma-assisted manufacture of optical fibers used in communications;
- Plasma synthesis of ultrapure powders used as ceramic precursors;
- Plasma spray deposition and thermal plasma chemical vapor deposition of high-temperature superconductors and refractory materials;
- Plasma welding and cutting; and
- Plasma sputter deposition of magnetic films for memory devices.

In the electronics industry (covered in greater depth in Chapter 3), plasma-controlled etching of materials provides the essential anisotropic etching for pattern transfer from a developed photoresist to the underlying structure; it is free from the undercutting that is characteristic of the alternative process, wet chemical etching. Such anisotropic etching becomes increasingly critical in the manufacture of progressively higher-density chips. There exists no other viable method to fabricate these structures. Plasma-deposited silicon nitride allows deposition at substrate temperatures between 200 and 350 ℃, much lower than the temperature that would be required for chemical-vapor-deposited silicon nitride. Because of the lower deposition temperature, this material can be deposited after completion of circuit features that would be damaged by a higher processing temperature. Plasma-deposited silicon nitride and silicon dioxide are the dielectric materials of choice for a variety of chip applications, including passivation coating for protection from chemical contamination and from mechanical damage, insulation between metal levels, masks to prevent oxidation or diffusion, and etch masks in multilevel resist structures.

Thermal plasma processing applications range from physical transformation of materials such as bulk melting in metallurgical plasma furnaces, metal cutting and welding, or powder melting during spraying, to driving chemical reactions, as in the reduction of oxides, in the synthesis of ceramic powders or films, or in the destruction of hazardous chemical wastes. Most of these plasma processes could not be replaced by other processes without sacrificing product quality and manufacturing efficiency. Thermal plasma generators have been designed for many diverse applications covering a wide range of operating power levels from less than 1 kilowatt to over 50 megawatts, and using various design principles. For processes of interest to the electronics industry, the rapid deposition of thick films using plasma spraying or thermal plasma chemical vapor deposition (TPCVD) are the processes of principal interest. The aerospace and the medical implant industries have come to rely on plasma spraying as a manufacturing process for a variety of coatings with controlled properties, such as corrosion resistance, porosity, and thermal conductivity. Plasma spraying is currently an $800 million per year business that is highly leveraged by the much larger jet engine and aerospace industries.

Applications of plasma spraying are pervasive in the aerospace gas turbine engine. Some newer engines may contain as many as 5000 components processed with plasma spray coatings. Thermal barter coatings (TBCs) provide the opportunity to use currently available compound materials to increase the operating temperature of turbine components without the use of increased cooling air. TBCs consist primarily of zirconia partially stabilized by yttria or magnesia. The thermal plasma spraying technique is ideally suited for applying multiple-layer TBCs at a reasonable cost. The main components currently being processed by thermal plasma spray techniques include turbine blades and vanes, burner cans, fuel vaporizers, stator vanes, and blade and reheat trough components.

Clearance control coatings (CCCs) generally consist of two components to provide the desired combination of integrity and abradability required to minimize tip clearance in rotating machinery, primarily gas turbine engines. Both metals and ceramics are used as the matrix, while additives include polymers, graphite, and other ceramics or minerals. A correctly designed and applied CCC will maximize efficiency by minimizing the loss between the blade tip and the casing's inner liner. Spray deposition of abradable coatings is especially suited to thermal plasma processing. The coatings are normally designed with predetermined porosity to enhance component rub characteristics. A limitation of these coatings is erosion resistance, which drops rapidly as porosity increases (porosity levels as high as 20 to 25 percent are common). Current composite abradable coatings for use in the compressor section consist of a porous top layer of a nickel matrix with graphite embedded as the lubricant, an intermediate denser ceramic layer of stabilized zirconia, a second ceramic layer, and a bond coat.

In thermal plasma chemical vapor deposition (TPCVD), deposition occurs with vapor phase precursors at atmospheric pressures. TPCVD has been used to deposit highly textured high-temperature superconductors, polycrystalline as well as homoepitaxial diamond films, and other ceramic films of potential interest to the electronics industry. This technology is on the verge of becoming commercial.

INTERFACE BETWEEN BASIC PLASMA SCIENCE AND APPLICATIONS

The interface between basic plasma science studies and technological applications is continuous. The challenge to industry is to improve system performance and to develop new products or processes. To meet this challenge, managers and support staff as well as engineers and scientists must understand the underlying physics and chemistry of the system, and they must develop the capability to deal with the multidisciplinary and diverse nature of the science. They will require science data bases, fundamental understanding of discharge and chemical processes, and diagnostic tools to make the necessary advances and meet the technological requirements of the future. Data bases needed to develop understanding of most plasma processing systems extend beyond data on homogeneous plasma phenomena to data on the coupling of the plasma with surfaces. Surface processes cause steep spatial gradients in plasma parameters, which greatly complicate data acquisition and system modeling, and alter the chemistry in the plasma. But surface processes are the raison d'etre of plasma processing and distinguish these plasmas from those found, for example, in studies of controlled nuclear fusion.

SCOPE OF THIS REPORT

Consistent with the charge to the panel by the Plasma Science Committee, this report assesses the current state and criticality of low-energy plasma science in materials processing, with emphasis on materials processing in microelectronics. In addition, it identifies key science issues and research needs in plasma physics and chemistry at surfaces. Finally, it presents the panel's recommendations regarding research funding, educational issues, and cooperation among universities, industry, and the national laboratories.

Plasma processing of materials is a broad field encompassing numerous technologies and industries. It is beyond the scope of this report to make meaningful assessments of each of the technologies and industries. In emphasizing the electronics industry, the panel addresses one of the largest industries in the world for which plasma processing is vital. It is also an industry in which leadership by the United States is being lost and an industry whose enabling science and technology are in need of nurturing. Thus Chapter 3 gives a fairly detailed account of the plasma processes used in the fabrication of today's and tomorrow's microelectronic circuits.

Although both glow discharges and thermal plasmas are used in the processing of electronic materials, most applications in fact exploit glow-discharge processing. However, thermal plasmas are used extensively in the deposition of emerging electronic materials such as diamond, silicon carbide, cubic boron nitride, and high-temperature superconductors. Although the panel has noted that the density-temperature parameter space is markedly different for these plasmas, diagnostic techniques, modeling approaches, and fundamental processes are often similar, and many of the conclusions presented here regarding science issues (Chapter 4) and educational issues (Chapter 5) pertain to both regimes.

This report should be viewed within the context set by the report *Materials Science and Engineering for the 1990s* (National Academy Press, Washington, D.C., 1989). Most if not all of the recommendations and findings in that report also apply here. Plasma processing is a key enabling technology for materials synthesis and modification. The recommendations made in this report necessarily emphasize the processing of materials for the electronics industry, and, in this sense, its coverage of new materials processing for the aerospace, automotive, and other industries is incomplete. The panel urges further assessment of these areas with respect to the role and criticality of plasma technology.

3

Plasma Processing In The Electronics Industry

The electronics industry is the modern "toolmaker" for the world economy and as such helps to generate jobs and improve productivity in most other industries. Automobiles, airplanes, telephones, dishwashers, and microwave ovens, to name but a few products, all have electronic components. The sophistication of our national defense relies on electronic components to provide missile guidance, antimissile defense, pinpoint bombing accuracy, and range finding, again to name but a few applications. In 1987 the U.S. electronics and telecommunications industries combined employed more people domestically (2,401,000) than did any other U.S. manufacturing industry. In fact, these industries provided nearly as many domestic manufacturing jobs in 1987 as did the metals (629,000), automobile (963,000), and aerospace (835,000) industries combined (see *Materials Science and Engineering for the 1990s*). Since 1976, the electronics industry has accounted for one of every eight manufacturing jobs in the United States. In 1990, total sales of electronics products reached $750 billion worldwide (Figure 3.1).

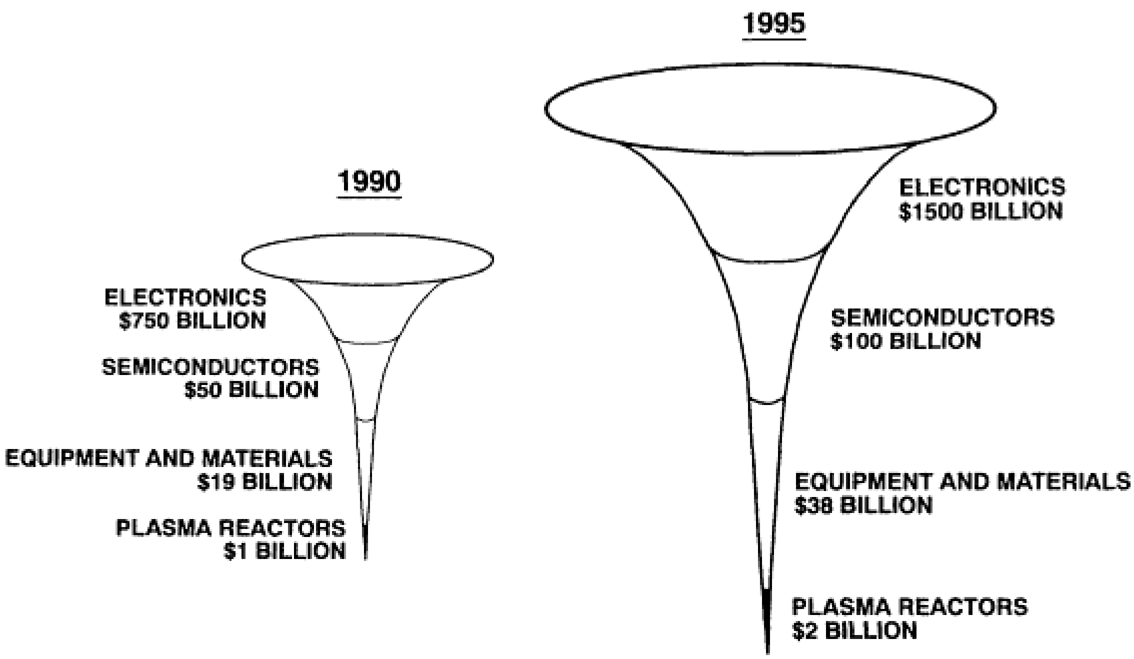

Figure 3.1
World electronics food chain (adapted from the National Advisory Committee on Semiconductors report, Preserving the Vital Base, Arlington, Va., July 1990). Although revenues are a small portion of the world electronics market, plasma technology is a critical component on which the industry rests. The electronics, semiconductor, materials, and equipment industries are all expected to double in the next 5 years. The plasma equipment industry is expected to keep pace with this trend.

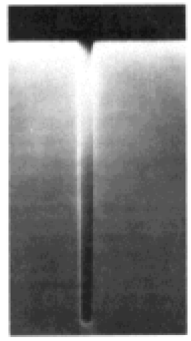

Figure 3.2
This trench etch (0.2 µm wide by 4 m deep) in single crystalline silicon shows the extraordinary capabilities of plasma processing. Such trenches are used primarily for device isolation and charge storage capacitors in memory devices. Only with plasmas can such features be fabricated economically. (Courtesy of Applied Materials, Inc.)

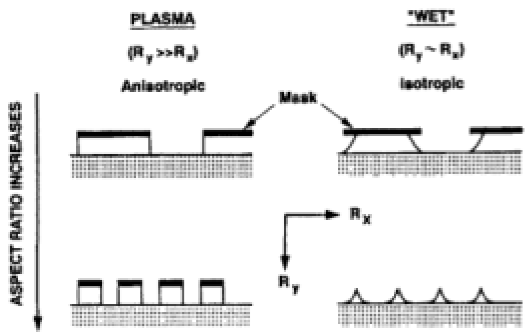

Figure 3.3
Schematic illustration of the difference between plasma (dry) and wet etching. Only plasma etching provides the needed anisotropic etching and high-fidelity pattern-transfer capability.

Feeding the electronics industry is the semiconductor industry, which had sales worldwide of $50 billion in 1990. Semiconductors are used in the fabrication of microelectronic integrated circuits or chips that are the principal components of electronic and telecommunication systems. Despite overall market growth, the United States consistently lost semiconductor market share throughout the 1980s and is expected to continue losing market share through the mid-1990s. In the world's largest semiconductor market—Japan—the United States has only a 10 percent share. Yet Japan has increased its U.S. market share from 5 to 30 percent since 1980.

Feeding the semiconductor industry is the equipment and materials industry, which had sales worldwide of $19 billion in 1990 (Figure 3.1). The ability to make large volumes of low-cost semiconductors depends directly on the quality of manufacturing equipment and materials. Plasma equipment and plasma processing are critical constituents in the equipment and materials industry. In fact, *the microelectronics industry would not exist as we know it today were it not for plasma processing*. For example, in the fabrication of 1-megabit dynamic random access memories (DRAMs), plasmas are used to "dry" etch patterns with vertical sidewalls and high aspect ratios (depth/width) into materials such as silicon, silicon dioxide, and aluminum. An example of a 0.2-mm-wide by 4-mm-deep (aspect ratio of 20) trench plasma etched in single crystalline silicon is shown in Figure 3.2.

To obtain high-density packing of microscopic circuit components, such *anisotropic* etching is essential. By contrast, wet chemical techniques used previously result in *isotropic* etching, where both vertical and lateral etch rates are comparable. As illustrated in Figure 3.3, only plasma etching can be used when aspect ratios approach or exceed 1; otherwise, the patterns to be transferred would be destroyed. Plasmas are also essential for depositing thin layers of dielectric materials, such as silicon dioxide and silicon nitride, that are used for insulation between conducting films and encapsulation of finished circuits to protect them from moisture and contamination. These films must be deposited at temperatures low enough so that the delicate circuit structure is not destroyed. Plasmas are also finding increasing usage in low-temperature cleaning of semiconductors and in other electronics applications, such as chip packaging and circuit board fabrication.

The primary use of plasmas in the electronics industry is in semiconductor chip manufacturing. In a typical semiconductor chip factory today, up to 30 percent of the equipment is plasma-based. As shown in Figure 3.4, device dimensions have consistently shrunk with time as technology has incrementally evolved. Besides finer device dimensions, another trend is to make use of stacked layers of materials for interconnection between devices: current devices make use of three levels of metals and insulators, whereas next-generation devices will use four, five, and six levels. These trends place increased demands and increased reliance on plasma processes for high-fidelity pattern transfer, low-temperature deposition, and gaseous cleaning. For example, in the fabrication of the interconnection structure, plasmas are used for deposition of dielectrics and metals, for etching contact windows and conducting patterns, and for cleaning surfaces between each of these steps. Just considering etching, the number of plasma steps more than doubled between the 4- and 16-megabit DRAM chip generations (Figure 3.5). As a result, the worldwide market for plasma etching and deposition equipment is rapidly expanding. In 1990, worldwide sales were about $1 billion, and by 1995 this should double in concert with the rest of the electronics, semiconductor, equipment, and materials industries (see Figure 3.1).

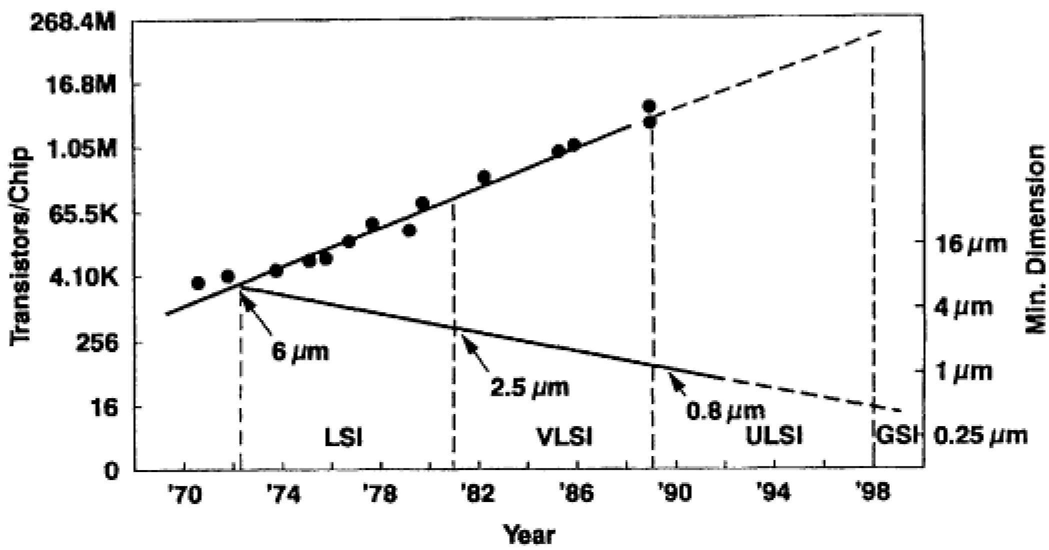

Figure 3.4
Increased level of integration and shrinking dimensions for integrated circuitry as a function of time. Such trends place both increasing demands and increasing reliance on plasma processing. (Adapted, by permission, from R. B. Fair, 1990, "Challenges to Manufacturing Submicron, Ultra-Large Scale Integrated Circuits," Proc. IEEE 78, 1687. Copyright © 1990 by IEEE.)

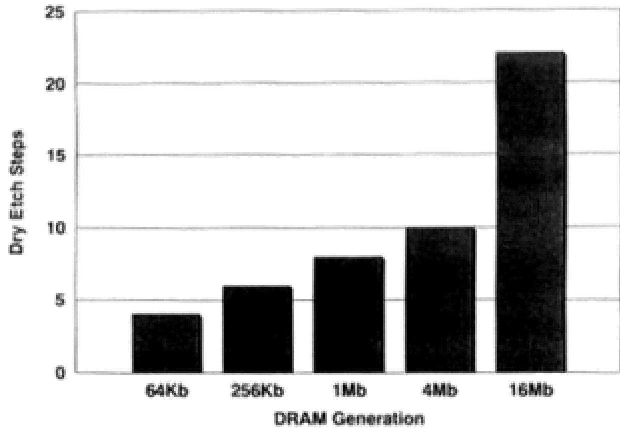

Figure 3.5
The trend toward increasing dry etch complexity, hence increasing use of plasma equipment, as the level of integration in memory chips increases. (Reprinted, by permission, from A. S. Bergendahl, D. V. Horak, P. E. Bakeman, and D. J. Miller, 1990, Cluster Tools, Part 2: 16Mb DRAM Processing, Semiconductor International, September, p. 94. Copyright © 1990 by Cahners Publishing Company.)

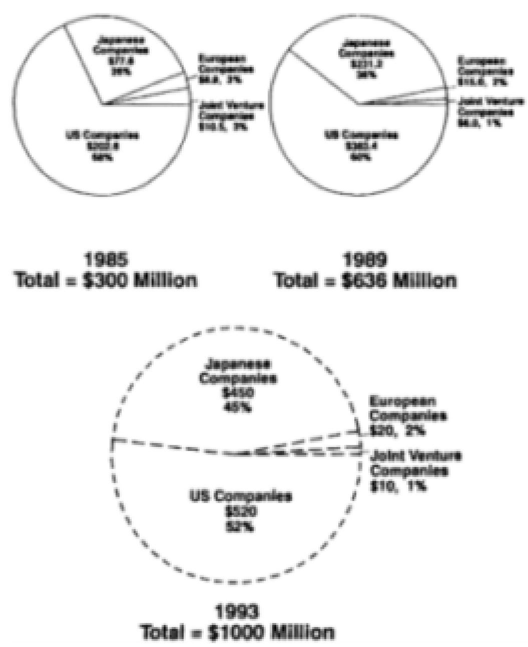

Figure 3.6
As illustrated for plasma etching alone, the United States dominates the world market in plasma process equipment but has steadily lost market share. This trend will likely continue as a result of Japanese ownership of the semiconductor market and the strong coupling between chip manufacturers and plasma equipment vendors in Japan. (Source of data for 1985 and 1989: Dataquest Newsletter, "U.S. Companies Dominate the Dry Etch Market, but Face New Challenges in the 1990s," September 1990, p. 1. The panel's projection to 1993 was obtained by linearly extrapolating from the 1985 and 1989 data. This extrapolation has been calibrated using similar data from earlier years.)

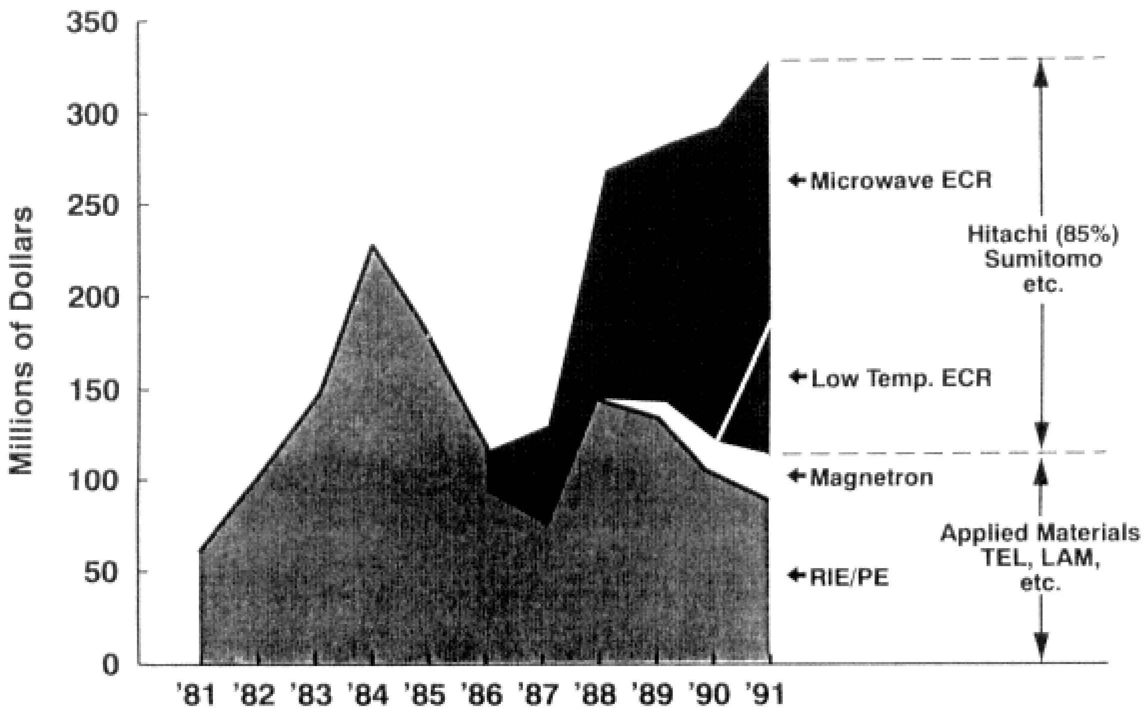

Figure 3.7
The market trend for dry etching equipment sold in Japan shows a clear trend toward increasing use of electron cyclotron resonance (ECR) plasmas. The primary vendors of such plasma equipment are Japanese companies such as Hitachi and Sumitomo. (Adapted from Nikkei Microdevices, May 1990, Nikkei Business Publications, Inc., Tokyo.)

Despite owning the majority of the plasma equipment market, the United States steadily lost market share during the 1980s. The trend projected by the panel for market share in plasma etching equipment is shown in Figure 3.6. During the 1980s, Perkin-Elmer, a former U.S. leader, dropped out of this field, and Materials Research Corporation (MRC), a former U.S. company, is now Japanese owned. There are perhaps many reasons for the declining U.S. market share in plasma processing equipment, but the fact that Japan is the largest market for semiconductor process equipment is perhaps foremost among them. Japan has also led in the development of advanced, electron cyclotron resonance (ECR) systems. For example, Hitachi and Sumitomo have substantially bolstered their market positions in recent years by supplying ECR etching and deposition equipment to Japanese semiconductor manufacturers (Figure 3.7).

The plasma equipment industry at first glance appears to be composed of many small companies. This is true for the United States, where semiconductor processing equipment suppliers are typically not aligned with large domestic chip manufacturers. As a result, research and development (R&D) funding for next-generation processing equipment is strained at a time when plasma equipment must quickly become more sophisticated to meet the challenges of next-generation devices. The total cost of wafers needed for a comprehensive equipment testing and evaluation program is estimated to be a daunting $600,000. Essentially no resources are available to generate fundamental understanding and data bases with which reactors and processes can be designed. New reactors and processes are developed solely by empirical means.

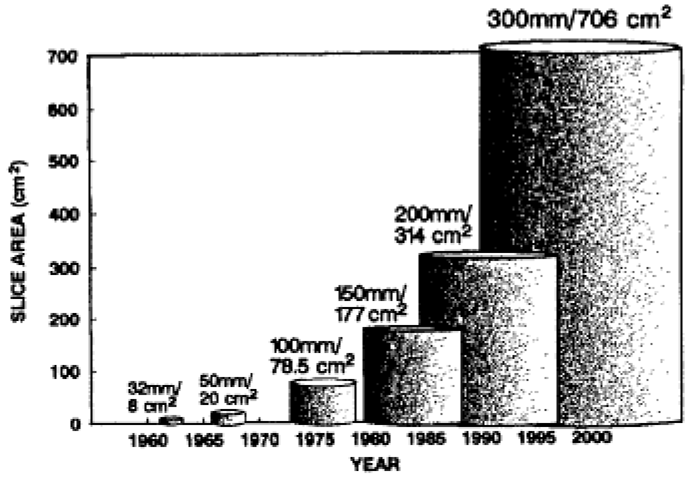

Figure 3.8
Trend in use of larger wafer slices for integrated circuit fabrication. Such trends place new demands on plasma reactor design and will likely lead to large development costs, since fundamental scaling laws that relate processes in small plasma reactors to those in large plasma reactors do not exist. (Adapted, by permission, from P. K. Chatterjee, 1991,"From VLSI to ULSI: The Subhalf-Micron Challenge," Proc. SPIE, 1392, 2. Copyright © 1991 by the Society of Photo-Optical Instrumentation Engineers.)

By contrast, most equipment development in Japan occurs by collaboration between chip manufacturers and equipment vendors. For example, data on process characterization and device yield are provided to the Hitachi equipment group by the Hitachi semiconductor group. NEC semiconductor groups have played a key role in developing the equipment for the Anelva ECR plasma system announced in 1990.

SEMATECH recognized the inability of independent companies in the U.S. equipment industry to invest in the industry's future and has begun to provide engineering support to equipment and materials suppliers (SEMATECH Annual Report 1989). However, SEMATECH's R&D efforts are largely focused on short-term improvements and do not adequately address long-term needs of the industry. In particular, they have placed little or no effort on plasma reactor design or plasma process simulation.

MICROELECTRONICS FABRICATION

Microelectronic devices are complex structures formed on the surface of a semiconductor wafer. Today's integrated circuits are composed of many millions of transistors that are microscopically wired together to form a circuit that covers an area of about 1 cm2. Several hundred chips are simultaneously fabricated on a 125- or 150-mm-diameter silicon semiconductor wafer. The wafer is then diced to separate individual chips that are packaged for installation on printed circuit boards for use in electronic systems such as computers, televisions, microwave ovens, automobiles, and aircraft. As we enter the 21st century, many billions of transistors will be incorporated into chips that are twice as large and fabricated on 200- or even 300-mm-diameter wafers (Figure 3.8).

The sizes of features that constitute the microscopic transistors are typically less than 1 micrometer, or about a hundredth the diameter of a human hair. This microstructure pattern is fabricated using subtractive processing, in which thin films are first deposited over the entire wafer surface and then removed selectively from only parts of the surface. Many steps in the subtractive patterning process already use plasmas, and in the future even more steps will use plasmas (see Figure 3.5).

Consider the electrical wiring that connects transistors, capacitors, resistors, and other elements of the integrated circuit (Figure 3.9). The fabrication sequence consists of:

1. Depositing a uniform metal layer (usually aluminum) over the entire surface (sputtering—a plasma process),
2. Coating the surface with a photosensitive polymer or photoresist,
3. Optically projecting a pattern onto the photoresist to alter the polymer's solubility,
4. Dissolving the more soluble portions of photoresist to create a polymeric mask on the metal (plasma development is used occasionally now and will be used more often in the future),
5. Etching the metal that is not protected by the mask (an essential plasma process), and finally
6. Removing the mask (a plasma process).

Plasmas are used in steps 1, 4, 5, and 6. Plasmas are also used in patterning the insulating layers and the underlying semiconductors. To fabricate such devices today, this sequence is repeated from 10 to 18 times. As we enter the 21st century, the number of steps and repetitions are likely to double, and plasma development of the resist will likely become routine. This complexity means that the yield on any single step must be much larger than 99 percent for the fabrication sequence to be economically viable.

Today's processes are developed using a combination of intuition and statistical optimization. The intuition enters in the initial choice of gaseous, reactant precursors, and other process variables such as pressure, flow rate, power, and surface temperature. Of course, this intuition is based on fundamental understanding of plasma science, and the better our understanding, the better our intuition and the more rapidly we can develop new processes.

Statistical methodologies (of which the Taguchi method is just one) provide prescriptions by which process variables are chosen with a minimum of experimentation. Interpolation schemes using functions of arbitrary form are then used to numerically determine "optimal" operating conditions that come closest to satisfying the specifications. This optimal space is then further explored experimentally with higher resolution to fine-tune the process. Such methodologies

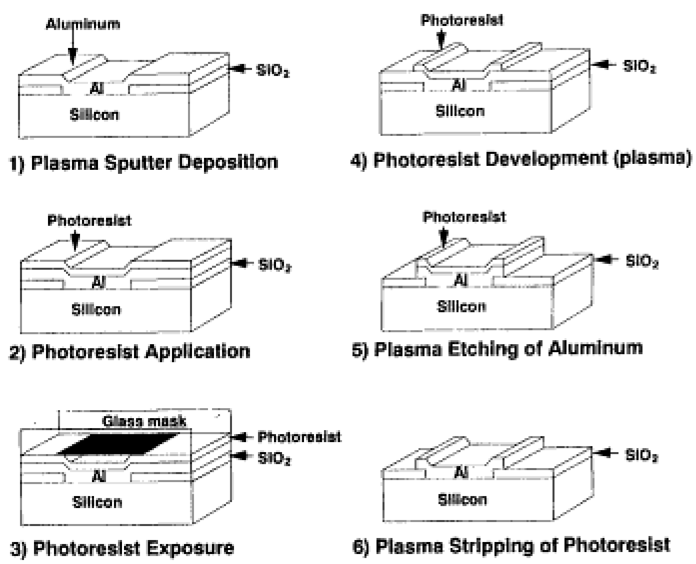

Figure 3.9
Subtractive processing scheme used in fabricating microelectronic integrated circuits. Steps 1, 5, and 6 routinely use plasma methods today; step 4 will see increasing use of plasma in the future. (Adapted from W. C. Till and J. T. Luxon, 1982, Integrated Circuits: Materials, Devices, and Fabrication, p. 259, by permission of Prentice-Hall, Inc., Englewood Cliffs, NJ 07632. Copyright © 1982 by Prentice-Hall.)

work best when the number of parameters and their ranges are most constrained: in other words, when the primary task is fine tuning. Only with insight based on fundamental understanding can we narrow the process variable space sufficiently and exploit statistical methodology for rapid process optimization.

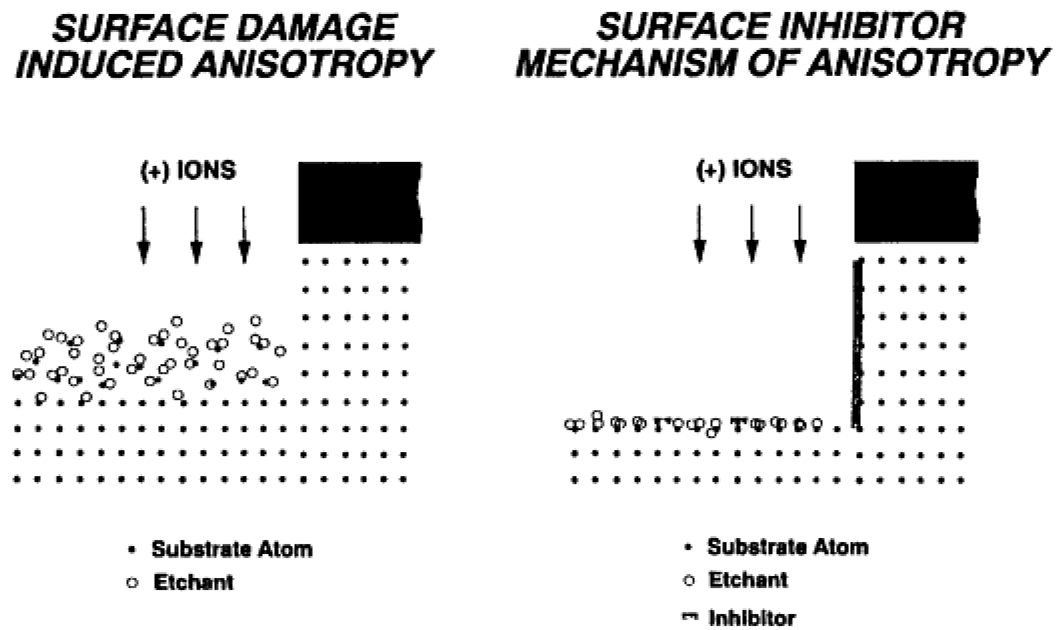

Figure 3.10
Schematic illustration of two (of many) proposed mechanisms for anisotropic plasma etching. In the first case, ions create a damaged surface that is then more reactive toward neutral etchants. In the second case, ions help to desorb etch-inhibiting species from the surface. In both cases, ion transport must be preferentially normal to the surface so that only the etch rate of the bottom surface is enhanced. (After D. L. Flamm and V. M. Donnelly, 1981, "Design of Plasma Etching," Plasma Chemistry and Plasma Processing 1, 317. Reprinted by permission of Plenum Press).

As we enter the 21st century, shrinking device dimensions and increased levels of integration will place greater and greater demands on plasma processing and its optimization. For example, processes under development today for manufacturing by 1994-1995 will require transfer of 0.35μm-wide features with less than a 0.035-μm linewidth loss (50 atoms on each side). By the year 2000, 0.25-μm structures are expected to be in production, and 0.1-μm structures will be under development with even more stringent constraints on linewidth loss (see Figure 3.4). Etching and deposition processes must also be uniform to better than 1 percent over 200- to 300- mm diameter wafers by the year 2000. This uniformity is equivalent to a variation of approximately 20 atomic layers across a wafer for a 0.5-μm film thickness. This represents more than a 5-fold improvement over today's capabilities, which are limited by gaps in fundamental understanding. For example, we do not understand how the pattern itself influences etching and deposition rates. To attain these goals and meet future needs, greatly improved understanding and control of the processing are needed to shorten the development cycle time and reduce the development expense.

PLASMA ETCHING

While previous generations of integrated circuits could be fabricated using wet, chemical etching techniques, the devices of today and the future cannot be made without using plasma etching to obtain the necessary pattern transfer fidelity (see Figure 3.3). For today's microtransistors, features such as gate electrodes or interconnection vias have widths that are comparable to the thin film thickness; therefore, to transfer the pattern with high fidelity, etching must be anisotropic, *i.e.,* much faster perpendicular than parallel to the surface. The silicon trench shown in Figure 3.2, used to isolate transistors on the chip or store charge in a DRAM, illustrates the anisotropic capabilities provided by plasma etching.

Linewidth losses of more than 10 percent cannot be tolerated if electronic devices are to operate as intended: for a 0.5-micron feature, that corresponds to less than 80 atomic layers on each side of the feature. In the laboratory, plasma processes have been used to etch features of only 200 atoms in width. However, the ability to control this etching reproducibly so that billions of features can be etched simultaneously on a 200-mm-diameter wafer with linewidth loss of less than 100 atoms is not currently achievable. The central issue in plasma etching is to control plasma process variables to obtain high anisotropy, high rates, and high uniformity over large areas without sacrificing selectivity or creating undue damage. Only by achieving such control can high-yield, high-volume, low-cost manufacturing be realized.

Anisotropy

The unique combination of reactive and charged species in the plasma permits rapid, large-area, anisotropic etching. Energetic ions enhance the reaction rate between active species in the plasma and the surface, clean the surface of etch-inhibiting or passivation layers, and stimulate desorption of volatile products. Illustrations of two of these anisotropic mechanisms are shown in Figure 3.10. The precise mechanisms for any given material system are not understood, but it is clear that the ions striking the surface must themselves be anisotropic, *i.e.,* traveling preferentially in a direction perpendicular to the surface. Ions are oriented and accelerated in a nonneutral region, called the sheath, between the plasma and the device wafer (Figure 3.11). The properties of this sheath are incompletely understood and yet are of paramount importance in controlling the plasma etching process.

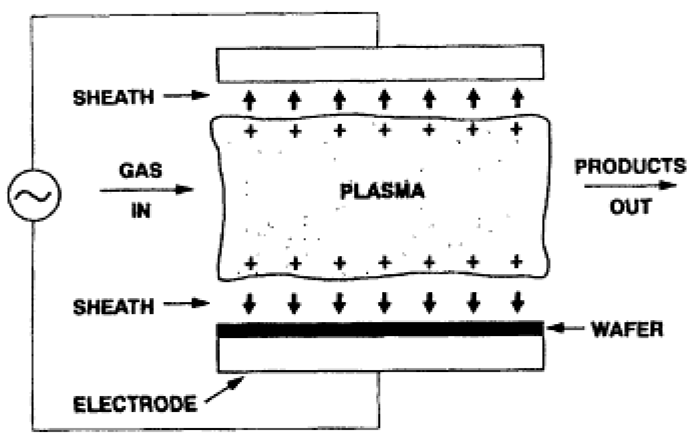

Figure 3.11
Schematic illustration of a parallel-plate, diode plasma reactor. Reactant precursor molecules, ions, and electrons are created primarily in the low-field plasma region. Electrons and ions are accelerated either toward or away from the device surface by the electric field established in the nonneutral sheath that separates the plasma from the surface. This type of reactor has been used in manufacturing for many years and is still in use today.

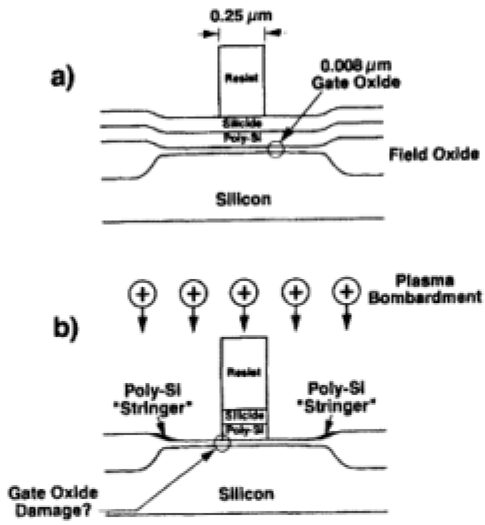

Figure 3.12
Schematic illustration of 0.25-µm poly-silicon/silicide gate structure used in metal-oxide-semiconductor field-effect transistors (a) before and (b) after anisotropic plasma etching. The gate oxide is only 80 angstroms thick and very sensitive to plasma-induced damage. Without planar geometry, over-etching is required to remove poly-silicon "stringers" near the field oxide isolating layer. (Adapted from J. M. Cook and K. G. Donohoe, 1991, "Etching Issues at 0.35 µm and Below, Solid State Technol. 34, 119. Reprinted with the permission of Solid State Technology.)

Selectivity

Material-selective etching is crucial for avoiding linewidth loss: ideally, the photoresist mask should not etch at all while the underlying film is being patterned. Similarly, after the film has been etched, the plasma ideally should not etch or alter the properties of the underlying thin film. Today, we do not understand the fundamental limits to selective etching in plasmas, but we do know that selectivity depends on both chemistry and charged particle bombardment. The same energetic bombardment that provides anisotropy in plasma etching tends to reduce selectivity, and a major challenge for the future will be to understand fundamental limits to both anisotropy and uniformity as a function of energetic particle bombardment.

We do know that the selectivities we can achieve today are inadequate for fabricating the devices of tomorrow. For example, aluminum can be etched typically 2 to 4 times faster than photoresist today. In just a few years, we will need to etch aluminum at least 10 times faster than photoresist to meet linewidth-loss specifications. The ability, which we currently do not possess, to selectively etch similar materials (silicon nitride with respect to silicon dioxide; poly-silicon with respect to metal silicides; silicon with respect to germanium) will create opportunities for low-cost, large-volume, fabrication of new, high-performance electronic devices.

Material selectivity in plasma etching is most demanding in etching gates for metal oxide semiconductor field-effect transistors (MOSFETs) where the gate oxide thickness will be less than 10 nanometers as device dimensions shrink. Consider the structure shown in Figure 3.12. Because of the topography, the silicide and poly-silicon layers must be over-etched to remove the "stringer" residue at the edge of the device, and selectivities for etching silicon or metal silicides with respect to silicon dioxide will have to be greater than 50 to 1 to maintain high yields.

Uniformity

Uniformity across a wafer must be maintained so that the underlying materials are not subjected to extended plasma exposure. The degree of uniformity required, therefore, depends partly on the selectivity of the etch. For higher selectivity, more overetch can be tolerated to compensate for poor uniformity. However, because the plasma can also damage underlying films, overetching must still be minimized. For example, for the gate structure shown in Figure 3.12 the plasma treatment must be gentle enough not to damage the thin gate oxide or the gate oxide-silicon interface.

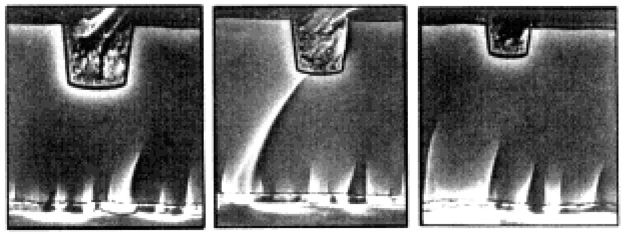

Figure 3.13
The effect of trench aspect ratio (width/depth) on trench etching rate: higher-aspect-ratio trenches etch more slowly than do lower-aspect-ratio trenches. Such effects have only recently been discovered and are not well understood. Because of the different etching rates, longer over-etching times are required, and the device may be more susceptible to plasma-induced damage. (Courtesy of D. J. Vitkavage and A. Kornblit, AT&T Bell Laboratories.)

While etching uniformity across a wafer can be engineered based on some knowledge of the fundamental science, nonuniformity on a microscopic scale is not well understood. For example, one of the reasons that there is not a single aluminum plasma etch process for all microelectronic devices is that the aluminum etching rate depends on the microscopic shape of the etched patterns. This problem is not unique to aluminum, and the trenches in Figure 3.13 illustrate how large-aspect-ratio trenches can etch more slowly than small-aspect-ratio trenches. This dependence was not appreciated until we entered the submicron etching realm in recent years. This sudden realization illustrates the potential problems that can occur as a result of incomplete fundamental understanding of etching processes. Ion bombardment, electron bombardment, reactive neutral flux, product desorption, and redeposition all appear to be important in determining the relative etch rates of trenches with different aspect ratios, and so a minimum physical understanding is needed to advance the technology.

Damage

Much work is needed to quantify plasma-process-induced device damage and relate it to processing conditions and reactor design. Plasma-induced damage can take many forms: "shorts" or "opens" created by particulate contamination; trapped interface charge; defects that migrate into bulk materials such as silicon or silicon dioxide; and mobile charge that alters the electronic circuit response. Ion, electron, and photon bombardment may all contribute to damage mechanisms, but little is understood about which factors dominate. The reactor design—materials, geometry, and electromagnetic fields—can have a dramatic effect on the level of contamination and the energies and types of particles impinging in device wafers. Since energetic bombardment of device surfaces is inherent to plasma processes, we must learn to optimize reactor design so as to minimize these effects if we are to increase the overall yield of chips in wafer manufacture.

New Materials

The advent of new materials in microelectronic device technology presents new challenges for plasma etching in the coming decade. For example, the effects of electromigration and stressvoiding in aluminum metallization suggest that aluminum will not suffice for the smaller geometries of next-generation devices. By the beginning of the 21st century, copper may be the material of choice for interconnection. But today, commercial etching processes for copper do not exist. Since there is no systematic methodology by which one designs a plasma process, a long and expensive empirical investigation will commence to find the right gases, the right process variables (power, pressure, surface temperature, and so on), and the right reactor to etch copper with sufficient speed, anisotropy, uniformity, and selectivity to make VLSI devices.

Similarly, the rapid progress in deposition of diamond, silicon carbide, and high-temperature superconducting thin films means that etching processes will be needed if these materials are to be used in new microelectronic devices.

While etching processes for compound semiconductors such as gallium arsenide and indium phosphide are well known, problems persist with respect to selectivity, uniformity, and damage. Etching of these materials is used to make novel devices such as two-dimensional quantum wires and one-dimensional quantum dots. Very little attention has been paid to the etching of II-VI compound semiconductors, such as cadmium sulfide and zinc slenide, but these materials will gain increasing importance in the coming century with the advent of integrated optoelectronic circuits. One of the challenges in compound semiconductor etching is preventing selective removal of one of the atomic constituents, *e.g.,* arsenic from gallium arsenide. This will require a detailed understanding of the surface chemistry under the influence of energetic ion and reactive neutral bombardment.

PLASMA DEPOSITION

Deposition of defect-free, strongly adherent, thin films over microscopic features is critical to microelectronic device manufacturing. But device structures are sensitive to temperature, and high-temperature deposition processes can cause problems. For example, after dopant atoms are implanted into silicon to make source and drain regions of the transistor, the total time that the wafer spends at elevated temperatures must be restricted to avoid dopant diffusion. As device dimensions shrink and dopant profiles become thinner, this wafer thermal budget becomes more restrictive, and so high-temperature deposition methods used today must be replaced by low-temperature plasma methods as we enter the 21st century.

Because of the nonequilibrium nature of low-pressure plasmas, high-temperature films can be deposited at low-temperatures, and films can be deposited with chemical composition and crystalline morphology that would be unattainable even under higher-temperature equilibrium conditions. In sputtering, a plasma is used to create energetic ion bombardment of a target electrode and thereby desorb the material to be deposited. This is how most aluminum thin films used for interconnection are currently deposited. In plasma-enhanced chemical vapor deposition (PECVD), precursor gases flow into the reactor and are decomposed by collisions with energetic electrons. Ion bombardment is used to improve adhesion and modify material properties, such as stress, crystallinity, and composition. For example, the final "capping" layer on both silicon and compound semiconductor devices is PECVD silicon nitride. Silane and ammonia are typical precursor gases. The proper stress to prevent film cracking and problems with reliability is obtained by using a plasma excitation frequency that enhances ion bombardment. The enhanced bombardment lowers stress by driving excess hydrogen from the film and promoting silicon and nitrogen cross-linking.

As in etching, such processes have been developed empirically. We need to design PECVD processes to tailor film properties while minimizing contamination and damage. Lacking is the fundamental understanding that links process variables such as gas composition, flow-rates, pressures, power, excitation frequency, and reactor design to film properties such as morphology, crystallinity, stress, composition, and electrical quality. Such understanding would enable more rapid replacement of high-temperature processes with low-temperature plasma processes and enable more rapid synthesis of needed new materials.

Planarization, Filling, and Interconnection

With the advent of four or more levels of interconnection, more than 50 percent of the cost of chip manufacture will be in the fabrication of electrical interconnects. Between interconnection levels are PECVD insulating films, such as doped silicon dioxide glass. Because the lithographic exposure only achieves maximum resolution over a limited depth of focus, these films must be fiat, or planarized, over the optical exposure area to construct higher levels of interconnection. This is sometimes accomplished using a repetitive sequence of plasma etching and plasma

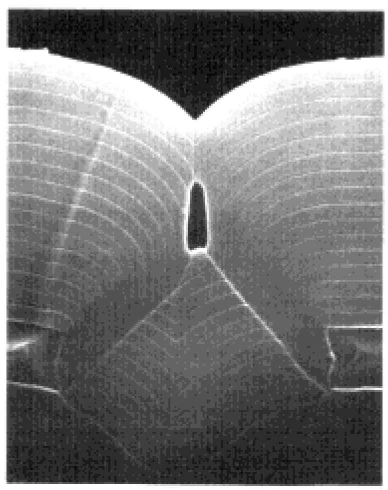

Figure 3.14
Scanning electron micrograph of plasma etched aluminum conducting lines after plasma deposition of silicon dioxide. Under these conditions, the common void or "keyhole" problem is observed. (Courtesy of K. Olasupo, AT&T Bell Laboratories.)

deposition in an integrated process chamber called a cluster tool. Today's processes have been developed empirically and are often plagued by particulate contamination and imperfect planarization. As device dimensions shrink, the constraints placed on planarity become more stringent: surfaces must be flatter over larger areas with fewer particulates.

Shrinking device dimensions coupled with higher aspect ratios also make filling of deep narrow trenches or spaces between conducting lines more difficult. As illustrated in Figure 3.14, voids are often created that affect device performance and create reliability problems. The conformality of the deposit and the filling of trenches and spaces can be controlled by changing plasma operating parameters. But, once again, the processes must be tediously developed by trial and error since we do not understand how plasma bombardment influences sticking probabilities or surface diffusion of deposition precursors.

Surface Modification

The use of polymeric interlayer dielectrics for both chip structures and chip packages helps reduce the interconnect capacitance, and thereby, increases system performance. A major problem with polymeric dielectrics, however, is poor adhesion to metal films. Empirically, plasmas have been found to help promote polymer-metal adhesion, but the fundamental mechanisms responsible are unknown. Quantitative work is needed that relates process variables to the chemical surface modification, and this surface modification to bonding strength.

New Materials

Arguably one of the greatest advantages of plasmas is their nonequilibrium nature that can be exploited in growing and depositing new materials. A sampling of such materials, how they might be applied, and which plasma methods are most promising is summarized in Table 3.1 and elaborated on below.

Table 3.1 Plasma Growth and Deposition of New Electronic Materials

Material	Application	Method[a]
Fluorinated polymers	Interlevel dielectrics	PECVD
Diamond	Heat sinks, transistors	PECVD, TPCVD
Silicon carbide	Heat sinks, transistors	PECVD, TPCVD
High-temperature superconductors	Interconnection, high speed	Spray, sputter, TPCVD
Compound semiconductors	Photonic, high speed	PECVD
Nanocrystallites	Data storage, photonic	TPCVD, sputtering, PECVD
Copper[b]	Interconnection	PECVD

[a] PECVD denotes plasma-enhanced chemical vapor deposition (low pressure); TPCVD denotes thermal plasma chemical vapor deposition (high pressure).
[b] Copper is currently not use in microelectronic devices.

In complex chips, circuit performance is often limited by the delay associated with the product of the resistance and capacitance of the interconnect "wiring." The capacitance can be reduced by using insulators with a lower dielectric constant than that of the silicon dioxide used today. Heavily fluorinated organic polymers are excellent candidates for such interlayer materials dielectrics and can be deposited using plasma methods. However, for each new deposition process, an empirical process development will be required because of our incomplete knowledge base.

Because of high thermal conductivity and large band gap, diamond and silicon carbide microelectronic devices are promising for high-speed, high-temperature, radiation-hard electronic applications. Imagine electronic devices functioning at hundreds of degrees Celsius without the need for cooling. Low-cost, microelectronic-grade diamond and silicon carbide devices would revolutionize electronic system design. Both PECVD and thermal plasma chemical vapor deposition (TPCVD) have been used to deposit diamond and silicon carbide films. PECVD, in particular, is attractive for the deposition of thin, uniform films for microelectronic applications, while TPCVD shows promise for high-rate deposition of thick films useful for heat sinks.

In TPCVD, the plasma is used to vaporize the stream of precursors while a cooled substrate is brought into contact with the plasma and nucleation occurs on the surface. Nonequilibrium conditions must be maintained in front of the substrate to avoid homogeneous nucleation in the boundary layer. Compared to conventional vapor-phase deposition techniques, the high energy density of the thermal plasma allows higher throughputs and higher film-growth rates. At the same time, much of the coating quality that can be obtained with low-pressure chemical vapor deposition and PECVD processes is also obtained with this deposition process. Further development of TPCVD is needed to enable uniform, reproducible coating of large areas with good adhesion.

Effective means of depositing high-temperature superconductors have been sputtering, plasma spraying, and TPCVD. Applications of high-temperature superconductors in microelectronics might include improvement of conventional devices by replacing metal interconnects and reducing circuit delay time and fabrication of Josephson junction logic devices to replace conventional transistor logic and achieve enhancements in computational performance. Much work must still be done to optimize the deposition methods and produce films with desired properties.

PECVD of compound semiconductors is another area of active research and promise. These materials are used in heterojunction and superlattice devices, and many of the quantum mechanical devices of the next century will require deposition of compound semiconductors. Plasmas offer rapid, large-area deposition capabilities, but films so far have been of relatively low quality when compared to those prepared by chemical vapor deposition or molecular beam epitaxy. Low-temperature deposition of these materials has generally been plagued by poor surface morphology and contamination. The first teams to overcome these problems by tailoring plasma parameters such as ion flux and bombardment energy and possibly by using pulsed plasma techniques will achieve leading positions in manufacturing and patents.

The properties of materials with phase structures on a nanometer scale (nanocrystalline) are different from those of normally available single-crystal, polycrystal, or amorphous materials because their aggregate atomic structure is unique. In nanocrystalline materials a significant fraction of the atoms are in grain boundary regions and thus experience a different atomic environment than in the bulk. In comparison with conventional polycrystalline structures, materials in nanocrystalline form exhibit large differences in saturation magnetization, density, and yield strength. In nano-ferroelectrics, nonlinear and highly anisotropic optical behavior is being explored. There are potential applications for such materials in data storage and photonic logic.

Currently, a technique similar to TPCVD is used in the plasma synthesis of nano-size particles. The substrate in TPCVD is removed, the plasma is quenched, and homogeneous nucleation occurs from a supersaturated vapor. The major technical issue in this technology is uniformity of the particulates with regard to size and phase, and collection without agglomeration. Reactive sputtering is also used to produce nanocrystalline materials. In view of the remarkable values for structure-related properties of these materials, it is important to develop approaches to allow scale up to large-quantity production. As with many areas of plasma processing this will require effective, reliable, and physically realistic process simulation models that can be used for control and optimization of process parameters.

PLASMA CLEANING

Wafers are repeatedly cleaned during microelectronic device fabrication. Partly, these cleanings are necessitated by exposure of the wafers to air and airborne particles between process steps, but cleaning is also needed because processes themselves generate contaminants that may lead to lower device yield or reduced long-term reliability.

While liquid cleaning processes have been reasonably effective, they will be inadequate for future generations of electronic devices, because liquids are more difficult to filter than gases. As device dimensions shrink, it becomes increasingly difficult to effectively clean submicron structures using liquid processes; perhaps worse, it is difficult to remove residual moisture when such features are effectively wetted. Such moisture is a potential source for post-manufacture corrosion and presents a serious reliability problem.

Corrosion of the wafer surface between process steps and after completion can be reduced or eliminated by dry cleaning, which removes contaminants that induce corrosion and prevents water vapor from contacting the surface. Processing in the 21st century will undoubtedly involve fewer air exposures as wafers will be transferred from process chamber to process chamber under vacuum or controlled gas ambients. The development of gaseous cleaning processes is critical to the advent of such process clustering. For these reasons, the industry is striving to eliminate as many cleaning steps as possible and substitute gaseous cleaning processes for wet processes.

The nonequilibrium properties of plasmas can be exploited in removing normally involatile residues from device wafer surfaces. Today, plasma processes are used to remove native oxides before deposition and photoresist after etching. However, in the latter case, the plasma stripping process is always followed by a wet chemical cleaning to remove refractory metals and mobile ions such as sodium and potassium. Effective plasma stripping of heavily ion-implanted resist is particularly difficult. Although removal of contamination by plasma processing has been demonstrated in the laboratory, the quantitative, fundamental understanding necessary to develop equipment and processes for manufacturing is lacking. Diagnostics to determine when cleaning is complete are needed to avoid overexposure of the wafer to the plasma.

Like liquid processes, plasma processes are notorious for their ability to generate particles. One of the major challenges facing the plasma processing community is to understand how particles are generated in plasmas and to develop methods that eliminate particle generation. If this can be done, the nonequilibrium nature of plasmas might be more fully exploited for in situ gas-phase wafer cleaning.

LOW-PRESSURE PLASMA REACTOR TECHNOLOGY

Plasma reactors and plasma processes are intimately intertwined. The geometric and electromagnetic design of plasma reactors directly influences the chemistry at device wafer surfaces; yet plasma reactors are designed empirically. We lack sufficient fundamental understanding to develop computer-aided design (CAD) tools with which we could eliminate time-consuming, costly trial-and-error equipment development. By the beginning of the 21st century, we could have such tools, provided a concerted program is implemented today to acquire the necessary diagnostic data and develop the numerical methodology. Such CAD tools will enable exploitation of nonequilibrium plasma properties in etching, depositing, cleaning, and synthesizing new thin films for microelectronic device manufacture.

Plasma reactor technology in the electronics industry has changed dramatically since the first application of plasma processing to photoresist stripping. Resist was stripped from 20 to 40 wafers simultaneously in a quartz tube called a barrel etcher. Radio-frequency (rf) excitation was used initially simply to avoid surface charging of insulating thin films. Since then it has been recognized that the excitation frequency can be used to tune ion energies, the degree of dissociation, and wafer attributes.

In the late 1970s and early 1980s, the American-invented hexode reactor found extensive use in microelectronics factories. In this geometry, a central hexagonal-shaped electrode is rf excited using capacitive coupling, and the surrounding bell jar is grounded. Again, batches of wafers are loaded; for example, 3 wafers of 125-mm diameter can be loaded on each face of the hexagon so that 18 wafers are simultaneously processed.

The planar, rf diode (see Figure 3.11) is another reactor that has been widely used in production. Batches of wafers are loaded onto one of the electrodes, either powered (the so-called reactive ion etch, or RIE, mode) or grounded (the so-called plasma etching mode). In a typical configuration, gases are injected through one of the electrodes and pumped out around the outside of the same electrode. The distinction made between RIE and plasma etching illustrates the importance of reactor design and wafer placement: in RIE, etching is usually more anisotropic but more damaging than in plasma etching. These differences do not actually result from the choice of which electrode to place the wafers on but rather from the geometry of the surrounding, grounded walls and the extent to which the plasma couples to them.

All these reactor types are used today in production, but none provides an ability to control plasma parameters—electron energy, ion energy, charge density, reactant density, and so on—independently and to modify properties of individual wafers. Because these geometries are inherently asymmetrical, wafers are not processed uniformly: rates vary both from wafer to wafer and within a wafer.

In the last 10 years many changes have occurred in the plasma processing equipment industry. The trends are clear and are expected to persist for the next 10 years: wafers will be processed one at a time using high-density plasma excitation that is decoupled from the wafer, and tight process control and clustered processing will be exploited in maintaining the integrity of sensitive interfaces between thin films.

Single-Wafer Processing

In the early 1990s, plasma processing is changing from batch operations to single-wafer operations with 150-mm-diameter wafers. By the beginning of the 21st century, single-wafer processing of 300-mm-diameter silicon wafers will be commonplace (see Figure 3.9). Larger wafer sizes are one approach to providing the additional throughput needed when one wafer instead of a batch is processed. Faster etching and deposition rates are also needed to compensate for the inherent throughput problem of single-wafer processing; this is one of the major motivations behind high-density plasma source development (see below).

To fully exploit the advantages of single-wafer processing, we need scaling laws for reactor design as we increase wafer diameter from 150 mm to 300 mm. Otherwise, each time we change wafer size, we will be compelled to repeat the time-consuming and costly equipment and process development cycle. No such design tools exist today.

Process Control

Single-wafer processing is more suitable for automated wafer handling and process control, but to exploit single-wafer processing capabilities we need tools for real-time process monitoring and control. Today, there is a dearth of plasma process monitoring tools, and few processes are actively controlled. Many plasma processes drift from desired conditions and, therefore, require continual retuning. Typically, the process drifts to marginal performance before corrective measures are taken, leading to suboptimal performance, lost throughput, and decreased yield.

Active feedback control is needed to improve process reliability and reduce process variability. Such control would lead directly to yield enhancement and reduction of on-line engineering for process maintenance. Currently, gas flow rates, pressures, and incident rf or microwave power are controlled independently of the surface or plasma properties. The only extent to which plasma processes are "controlled" is through endpoint detection schemes that signal the beginning of the overetch period; the process is completed at a specified time after "end-point." With automatic feedback control based on real-time detection of the plasma and wafer state, the process conditions could be maintained at the optimal conditions.

Process models are required to relate diagnostic data to process control variables such as pressure, flow rates, and power and to process yield. For example, a change in wall-surface recombination could create excess isotropic etchant, *e.g.,* atomic chlorine, that in turn increases the etching rate but decreases the etching anisotropy. To make the necessary process corrections in this scenario, the anomalously high atomic chlorine concentration must be detected and related via the process model to an unacceptable loss in pattern transfer fidelity. The corrective action will depend on the cause of the increased chlorine concentration and the coupling between plasma parameters, anisotropy, rate, selectivity, uniformity, and damage. Development of control algorithms for these applications is currently in its infancy.

New Plasma Sources

As feature sizes for integrated circuits continue to decrease, the limits of conventional rf plane parallel systems are rapidly being approached. Because of smaller feature widths and thinner film thicknesses, devices are more sensitive to and can tolerate less damage caused by energetic ion bombardment, ultraviolet radiation, and particulate contamination. Except for triodes, conventional plasma reactors do not separate plasma generation from charged-particle transport, and it is not feasible to tune ion energy independently and thereby minimize damage without also affecting rate, selectivity, uniformity, and anisotropy. Hence, there has been considerable interest in high-density, low-pressure, magnetized plasma sources, for which plasma generation is wholly or partly separated from the processing region. The independent control of ion energy and plasma density promises a wider window for process optimization, reduction of particulate contamination, and minimization of ion-, electron-, and photon-induced damage. The magnetic confinement and resonant mode excitation used to create high plasma and reactive particle densities are required for single-wafer applications. Magnetic fields also modify ion bombardment energies and can be used as another control parameter for process optimization. However, the application of magnetic fields makes modeling, design, and control of plasma processes significantly more challenging.

Magnetic Confinement

In some of the latest generation of etchers used on production lines today, a uniform direct-current magnetic field is applied parallel to the wafer surface to raise the plasma density and reduce the ion bombardment energy. To achieve the required time-averaged plasma uniformity across the wafer surface, the field direction is rotated electrically with a period short with respect to the processing time. Most advanced plasma reactor development in the United States is focused on such magnetically enhanced reactive ion etching (MERIE).

In Japan, on the other hand, efforts are widely focused on electron cyclotron resonance (ECR) sources (see Figure 3.7). In these systems, one or more circular coils generate a nonuniform, axisymmetric magnetic field inside a source chamber, and 100 to 5000 watts of 2.45-GHz microwave power is absorbed at ECR within the chamber producing a high-density plasma. Other high-density, magnetized reactors include distributed ECRs (pioneered in France), helicons (pioneered in Australia), and surface wave sources (pioneered in Canada and Europe). Other high-density sources receiving attention in the United States are helical resonators and inductive rf sources.

Uniformity of the plasma and radical fluxes to the wafer are critical issues. To control and enhance uniformity, permanent magnets can be arranged around the process chamber to create a magnetic-field-free volume where the wafers are processed. Alternatively, an additional electromagnetic coil can be placed near the wafer and be operated either in a magnetic mirror or magnetic cusp mode. The overall magnetic configuration can be complicated; however, the configuration and the plasma response are accessible to measurement and modeling for the design of processes.

Each of these sources and downstream configurations has its own advantages and disadvantages, and it is likely that no one configuration will be used for all processes. Until we attain a detailed understanding of the role that source geometry and electromagnetic design play in materials processing, the best reactor choice for a given process will not be obvious and will necessarily be based on empirical, trial-and-error experimentation. Figure 3.15 illustrates the dilemma facing semiconductor manufacturers today in choosing the plasma equipment necessary to make next-generation devices. Buying and evaluating each of the choices are prohibitively expensive.

Downstream Processing

The device wafer can be placed either inside the source or in a downstream process chamber. In either case, an independent rf bias voltage can be applied to tune ion energy and flux independently from plasma generation. For example, in photoresist stripping, the elimination of ion bombardment and photon flux is desirable, and the downstream configuration is preferred. In PECVD, chemical precursors can be introduced downstream of the plasma to control the composition of species impinging on the wafer surface. Remote plasma processes are less dependent on wafer state and, therefore, are more compatible with robust, flexible manufacturing (see below) in which different device codes can be processed without reengineering the process each time.

Modulated Processing

Modulated plasma processing is a hybrid approach between remote and direct processing that has to date been implemented in only rudimentary ways. For example, during the over-etch period, the gas chemistry may be switched or modulated to improve selectivity at the expense of anisotropy. Japanese researchers have led this hybrid approach in application to anisotropic etching, whereby an etchant and an etch-inhibitor are alternately introduced into the plasma. Plasma power modulation also appears to be an effective means of controlling particulate generation by periodically extracting small, negative particle precursors.

A related method developed in Japan is so-called digital plasma processing, in which one atomic layer is etched or deposited at a time. In deposition, digital plasma processing is like molecular beam epitaxy except that the growth need not be epitaxial. The technique usually employs sequential process steps, one of which, say an adsorption step, is kinetically limited to one atomic layer. The main virtue of this technique is insensitivity to nonuniformities in process conditions; *e.g.,* the growth rate becomes insensitive to gas flow because of the kinetic limitation to adsorption of gas onto the surface. This allows precise control over the thickness of the material deposited or removed. It also allows atomically sharp interface fabrication, thin-layer deposition, and doping profiles. The main disadvantage of the technique has been low throughput. Potential applications for this technique include fabrication of very narrow quantum well structures, surface cleaning and preparation, and etching where extreme selectivity is required.

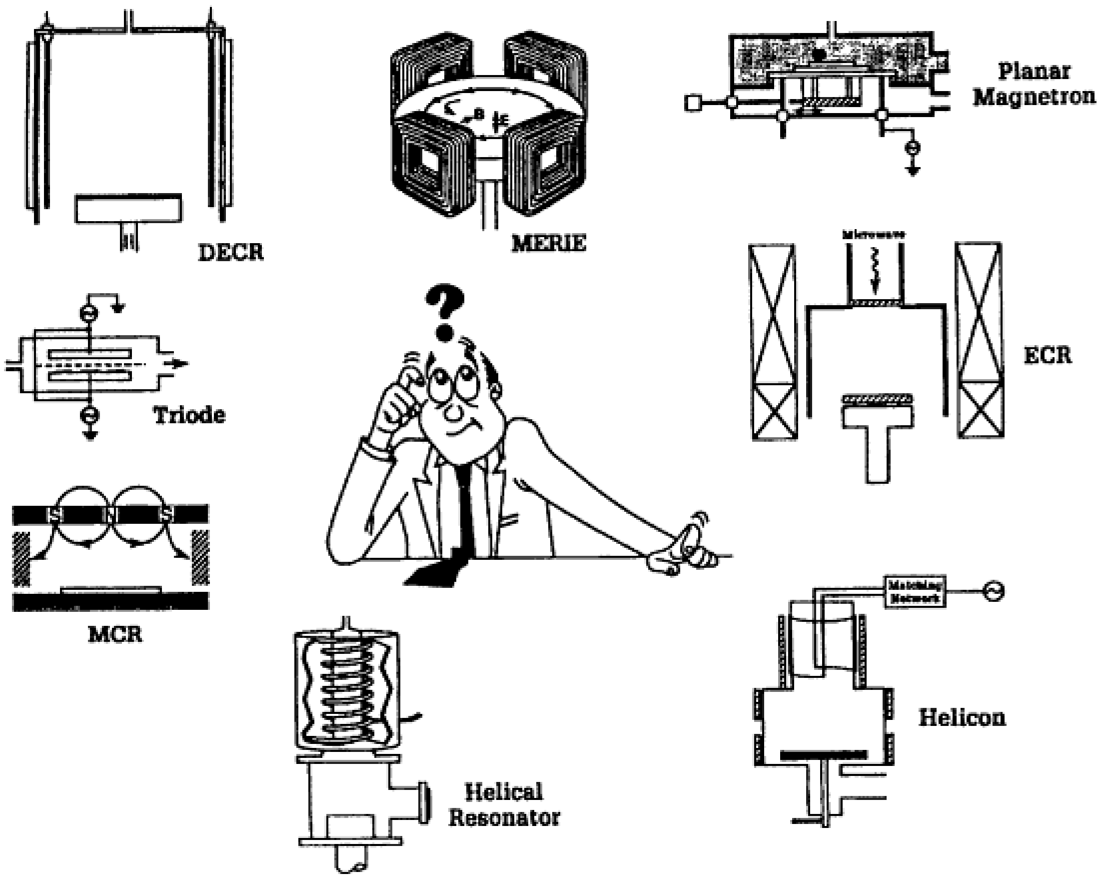

Figure 3.15
Semiconductor manufacturers are faced with the dilemma of choosing plasma process equipment from a wide variety of configurations but without fundamental understanding of how designs will affect processes and meet device fabrication specifications. Since the choices are not obvious but are critical, the evaluation process will proceed by costly, time-consuming trial and error. A subset of the available choices are shown here, going clockwise from the upper left: distributed electron cyclotron resonance, magnetically enhanced reactive ion etcher, planar magnetron, electron cyclotron resonance, helicon, helical resonator, magnetically confined reactor, and triode. (Based on data from D. L. Flamm, 1991, "Trends in Plasma Sources and Etching," Solid State Technology, March, p. 47.)

Clustered Processing

Microelectronic device wafers are processed in clean rooms to minimize ambient exposure to particulate contamination. As device dimensions shrink and we fast approach the practical and economic limits of clean room technology, particulate contamination becomes an even more serious problem. For example, 0.1-μm-diameter particles that were innocuous for 1.0-μm-linewidth device structures become "killer" defects for 0.3-μm-linewidth devices.

To minimize particulate contamination and preserve the integrity of thin-film interfaces, it is desirable to link processes together. A cluster tool consists of a group of process chambers arranged about a wafer handler that passes wafers from chamber to chamber. Thus, wafers can be transferred from reactor to reactor without being exposed to and contaminated by the ambient. Today, plasma cluster tools are used in manufacturing primarily to increase throughput for single-wafer processes, etch multiple layers sequentially, or etch and deposit sequentially for planarization. The development of gaseous cleaning processes to remove photoresist, native oxides, process damage, and wafer contaminants is essential to fully realize the benefits of clustering. In addition, reliable, robust plasma etching and deposition processes with real-time, *in situ* diagnostics are needed to avoid wafer inspection between processes.

A major impediment to development of cluster tools is their cost. In 1990, a three-chamber cluster tool with wafer load chamber and central wafer handler typically cost $1 million to $2 million. Costs will continue to escalate as cluster tools and their process chambers become even more sophisticated. However, the advantages of process clustering compared to single-chamber processing are likely to outweigh the high cost of ownership.

THERMAL PLASMA REACTOR TECHNOLOGY

Thermal plasma generators that are being used in the electronics industry are plasma spray torches and TPCVD reactors. Direct current plasma spray torches consist typically of a rod cathode with a conical tip inserted into the converging section of a nozzle anode. The cathode material is usually tungsten with a low-work-function material such as thorium oxide added to increase thermionic emission. The cylindrical anode is usually made of copper and is water cooled. The plasma gas is introduced at the base of the cathode, usually tangentially to provide a swirl to stabilize the cathode attachment and to move the anode attachment to distribute the heating by the arc attachment. The plasma exits the anode nozzle with peak temperatures between 12,000 K and 16,000 K, and peak velocities between 500 m/s and 1,000 m/s. The most frequently used plasma gases are argon, argon-helium, or argon-hydrogen mixtures. A typical nozzle diameter is 6 mm, the arc length is on the order of 20 mm, and power levels range from 40 to 80 kilowatts. The powder is introduced into the plasma gas flow either through a hole in the anode wall or through an injection tube in front of the nozzle exit. The particles are accelerated and heated by the plasma gas and then rapidly solidified upon hitting the substrate. Thick films can be rapidly deposited with close to the theoretical density of almost any metal or metal alloy, and of many ceramic materials, including high-temperature superconductors.

The major issues in plasma spraying are the reliability of the coating process and the dependence on powder characteristics. This translates into the plasma science issues of (1) understanding the arc anode attachment instability, (2) controlling the plasma jet fluid dynamics, and (3) being able to describe the plasma-particle interaction.

Major recent developments are the low-pressure plasma spray process in which the plasma jet exits into an evacuated chamber with supersonic velocities; the development of new nozzle geometries to better control the atmospheric pressure plasma jet; and reactive plasma spraying, in which the metal alloy or the ceramic to be deposited is formed by reacting the spray powders either with powders of a different type or with a gas environment. Another development makes use of radio frequency-induction plasma torches to heat the powders. In rf plasma spraying, the gas and the particle velocities as well as the plasma temperatures are lower than in direct-current spray guns, but the longer particle heating times will assure good melting.

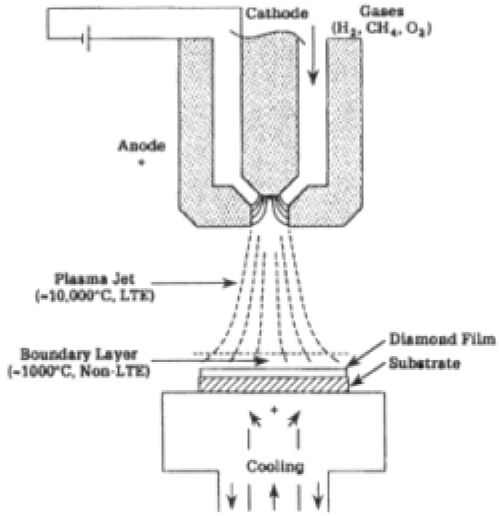

Figure 3.16
Schematic illustration of a thermal plasma chemical vapor deposition torch used for depositing electronic materials.

There are several designs of plasma generators for TPCVD (Figure 3.16). In this process, a good mixing of the vapor phase reactants with the hot plasma is necessary to provide a uniform vapor mixture in front of the substrate. The substrate has to be in intimate contact with the plasma and has to be cooled. This way a nonequilibrium boundary layer between the plasma and the substrate can be maintained without nucleation occurring in the boundary layer. Since the plasma is at or close to atmospheric pressure, the deposition precursor densities and hence the deposition rates can be significantly higher than with low-pressure deposition processes. Radio frequency-induction plasma torches have been probably the most favored plasma-generation method for TPCVD, because they provide a plasma flow with moderate velocity and moderate energy density and uniformity over a larger surface area. However, there are also several DC TPCVD systems in use in which the uniform mixing of the reactant vapors is attained in different ways, for example in a high-temperature flow channel, or by use of multiple torches similar to plasma spray torches.

The major technological issue in TPCVD is control of the conditions in the boundary layer in front of the substrate. The high-temperature chemical kinetics proceeding in this boundary layer are little understood.

TOWARD FLEXIBLE MICROELECTRONICS MANUFACTURING

Custom-designed and custom-manufactured chips, so-called application-specific integrated circuits (ASICs), account for more than 20 percent of worldwide chip production today. Between now and 1994, ASIC production is expected to grow at a compound annual rate of 16 percent. In 1989, U.S. companies accounted for 52 percent of worldwide ASIC shipments (M. J. Boss and A. Prophet, 1989, "U.S. ASIC Supplier at the Crossroads," *Solid State Technology,* July, p. 33). Unlike DRAM production, in which large volumes of identical chips are manufactured for each design rule generation, ASIC device codes are fabricated to customer specifications and are manufactured in small volumes. Therefore, the ASIC manufacturer cannot afford to invest heavily in new processes and new processing equipment each time a new order is placed. The future ASIC market will belong to the flexible manufacturer.

Flexible manufacturing is the fabrication of integrated circuits using a common set of processes and equipment to manufacture many different circuit designs. To achieve this goal, it is imperative to understand how rate, uniformity, anisotropy, selectivity, and damage depend on microstructure and film composition. It is not likely that processes will be made independent of microstructure or film composition; therefore, processes will have to be pretuned for each device wafer code.

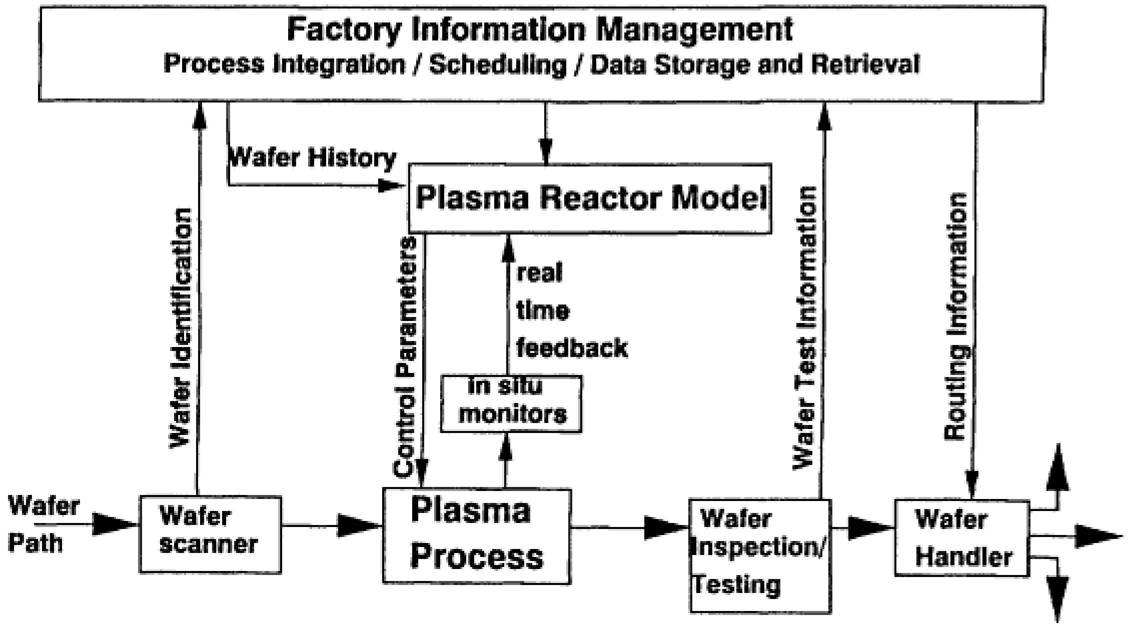

Figure 3.17
Schematic illustration of future flexible plasma processing with real-time process control. Fundamental studies are needed to provide in situ monitors and plasma process models that relate diagnostic input to wafer attributes and wafer attributes to control variables.

Consider the scheme shown in Figure 3.17. Each wafer is marked and its process routing determined by a "smart" scheduler. Based on previous process history and device design (microstructure), each process step is pretuned to the predicted optimal settings. Diagnostics are used to monitor the process in real time, to provide input for feedback control, and to terminate the process if it diverges from specifications. After processing is complete, a fraction of the wafers are automatically inspected to assure process integrity and to refine further the process model.

To incorporate plasma processes into such a flexible scheme, diagnostics are needed to monitor both the plasma and the wafer states. Process models must be developed: these might be expert-type systems based on fundamental insights and scaling laws, or perhaps neural network controllers where the complex plasma-surface relationships have been "learned" by a machine.

FINDINGS AND CONCLUSIONS

The U.S. electronics industry is a vital part of the American economy and an integral part of our national defense. Plasma processing is a keystone in this industry. In the manufacture of integrated circuits, plasma etching is the only economically viable method for high-fidelity transfer of microscopic patterns. Similarly, plasmas are used extensively for depositing insulating and conducting films at temperatures low enough to avoid compromising device performance. Plasmas are also used for cleaning and modifying surfaces.

As microelectronic device dimensions continue to shrink during the next 10 years, plasma processing will be used with increasing frequency, while greater demands will be placed on plasma processes. The successful fabrication of future generations of integrated circuits will require dramatic improvements in the anisotropy, selectivity, and uniformity of etching; improved planarization and conformality in deposition; new materials to meet device performance and reliability requirements; and reduced process damage and contamination. To meet these challenges, new processes and new reactors are needed.

Plasma processes in use today have been developed using a combination of intuition, empiricism, and statistical optimization. Design tools such as numerical simulation codes or even expert systems do not exist for plasma processes because of fundamental gaps in understanding. With the unprecedented demands now being placed on plasma processes, it is unlikely that the traditional approaches used in process development will continue to satisfy our needs. Tools are needed to relate process variables to wafer attributes, modify existing processes, and design new processes.

Plasma reactor design is intimately intertwined with plasma processes, but we again lack computer-aided design tools for new plasma reactor design. We are also unable to transfer processes from one plasma reactor to another or to scale processes from a small to a large plasma reactor. Until we understand how geometry and electromagnetic design affect material properties, the choice of reactor for a given process will not be obvious. Without physical understanding leading to computer-aided design tools, only costly empirical, trial-and-error experimentation will be available to provide the necessary guidance.

The United States has lost the lead in new plasma reactor and process development, and the health of the American electronics industry is seriously threatened as a consequence. One reason for this precarious situation is the relationships between chip manufacturers and their processing equipment suppliers. In Japan, most equipment development occurs by collaboration between chip manufacturers and equipment vendors. In the United States, on the other hand, semiconductor processing equipment suppliers are small and typically unaligned with chip manufacturers. As a result, critical process information is not efficiently fed back to equipment builders, and R&D funding for next-generation processing equipment is strained.

As custom-designed, custom-manufactured chips (application-specific integrated circuits, ASICs) gain a larger market share, the future microelectronics market will no longer be dominated by memory chips. But customization at low cost means that the ASIC manufacturer cannot afford to invest heavily in new processes and new processing equipment each time a new order is placed. The future ASIC market will belong to the flexible manufacturer who uses a common set of processes and equipment to manufacture many different circuit designs. Such flexibility in processing will result only from real understanding of processes and reactors.

4

Scientific Foundation of Plasma Processing

To meet the specifications for future generations of electronic devices, we need new and/or improved plasma processes, plasma reactors, and process control. A prerequisite to designing successful, economically viable manufacturing processes is a comprehensive understanding of the fundamental physical and chemical interactions that take place in plasma reactors. In the next 10 years, an integrated approach that combines empiricism with *in situ* diagnostics and relies more heavily on fundamental understanding will be most effective in developing new plasma processes (Figure 4.1). For new plasma reactors, a concerted effort can bring the advantages of computer-aided design.

To date, technological progress has been accomplished mainly as a result of uncompromising empiricism. However, in limiting the vast parameter space that must be empirically explored, the technologist routinely uses basic science data and insights into fundamental processes that were gained from previous investigations. The input of basic science to plasma processing has been to discover and investigate phenomena, develop measurement techniques, demonstrate possible reaction mechanisms, provide conceptual frameworks, and show correlations between experiments in plasmas and experiments in a more controlled environment. Below is a sampling (by no means exhaustive) of important contributions to plasma processing from basic science.

- Demonstration that ion-enhanced chemical reactions are an important anisotropic etching mechanism;
- Elucidation and demonstration of selectivity mechanisms in etching reactions;
- Understanding of fundamental causes of material loading effects in etching processes;
- A conceptual framework for understanding the influence of additive gases (such as oxygen and hydrogen) on rate, uniformity, anisotropy, and selectivity during etching;
- Measurement of appropriate rate constants and cross sections that are used to model technologically important discharges;
- Development and use of diagnostic techniques such as mass spectrometry, optical actinometry, laser-induced fluorescence (LIF), and Raman spectroscopy to measure species concentrations in the plasma;
- Use of light scattering to show that plasmas produce particles that reduce device yield.
- Use of optical techniques to measure electric fields responsible for charged-particle transport to and from device surfaces;
- Use of diagnostic techniques to investigate the influence of excitation frequency on discharge characteristics and thin-film properties such as stress;
- Development of numerical techniques and analytical theories for modeling of technologically important discharges;
- Measurement of sticking coefficients for surface reactive species; and
- Investigation of etching and deposition mechanisms using beams of reactive atoms, molecules, ions, electrons, and photons impinging on well-defined surfaces under a controlled environment.

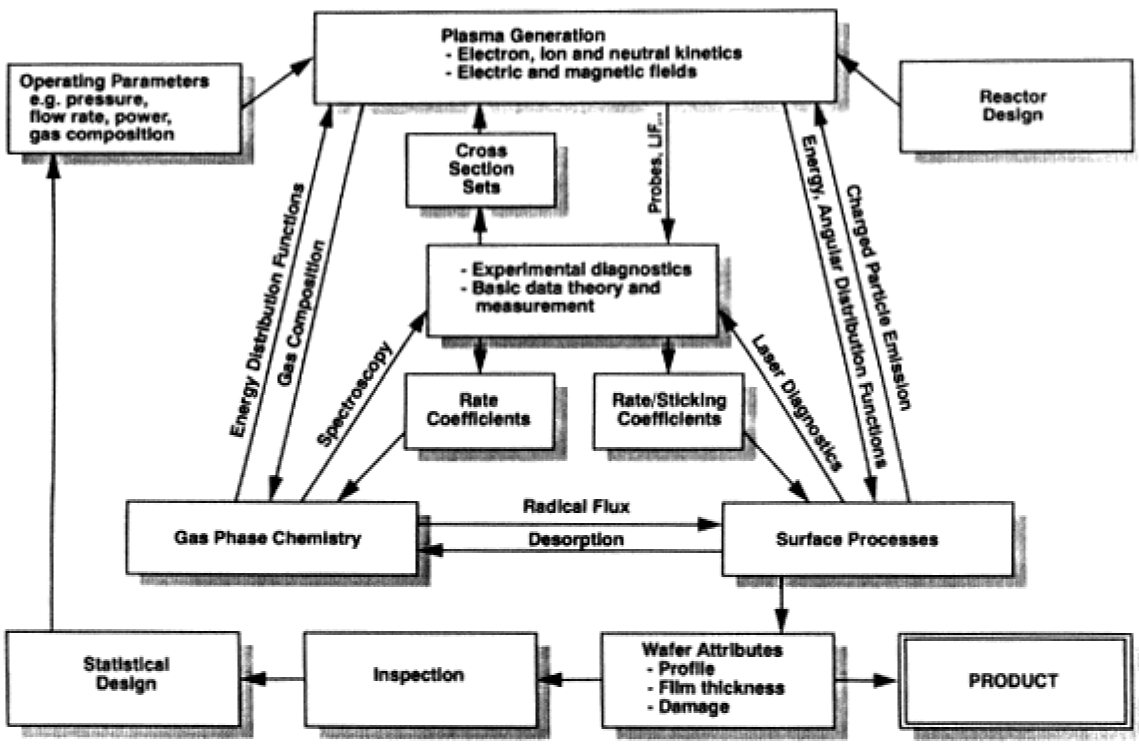

Figure 4.1
Schematic outline of a process simulator used in conjunction with statistical optimization and diagnostics to develop plasma etching and deposition processes. Given a reactor design and initial operating parameters— which could come from computer-aided design and expert system tools—the simulator makes use of basic cross-section and rate coefficient data to predict wafer attributes. Diagnostics of the plasma and surface are used to limit the process model and provide feedback as to its accuracy. Fine-tuning of the process is accomplished using statistical design methods.

These contributions have come from relatively small groups of researchers working in industrial, national, and university laboratories in the United States. However, the efforts have been almost totally uncoordinated. For example, diagnostic measurements are made on one material system and reactor design while simulations are performed on a different material system and reactor design. Furthermore, production reactors represent yet another technology. As a result, basic science studies have contributed greatly to our collective intuition but little to our ability to quantitatively simulate processes or design reactors.

The synergism of scientific intuition and the empirical method has been successful for the fabrication of the relatively simple and modest-density microelectronic devices of the 1980s. However, the empirical relationships that are used today to relate wafer attributes (film thickness, anisotropy, uniformity, damage, residues, and so on) to process variables (e.g., power, gas composition, flow rates, pressure) are equipment and process specific and cannot be applied to the new equipment and processes needed for future generations of devices. The recalibration and reoptimization of manufacturing process steps by empirical means alone is inefficient and costly.

Unfortunately, the complexity of plasma processes and the lack of fundamental understanding make detailed, quantitative process simulation based on first principles seem unlikely in the near future. However, scaling laws based on fundamental plasma science could readily be used in transferring processes from reactor to reactor or from one processing regime to another. Fundamental knowledge could also be incorporated into expert system algorithms that systematically guide engineers in making wise decisions when developing new processes and thereby limit the domain for statistically aided empirical optimization.

For plasma reactor design, computer-aided design (CAD) tools can be developed from understanding based mostly on first principles. Such tools will require calibration against an experimental standard to enable quantitative prediction of charged-particle and neutral fluxes to surfaces. However, they would be invaluable in comparing the performances of competing reactor designs without having to "cut" metal.

What prevents the creation of such scaling algorithms, expert systems, and design tools? There are clearly gaps in our fundamental understanding of plasma transport, surface processes, and plasma-surface interactions (Figure 4.1). For example, increased understanding of plasma-surface reactions requires knowledge of (1) the flux, energy, and type of species incident on the surface; (2) the flux, energy, and type of species leaving the surface; (3) the concentrations of species on the surface; and (4) the surface electronic and geometric structure. No complete set of such information is available for any plasma-material system. The only reliable information on etch products is inferred from experiments conducted outside the plasma, and virtually nothing is known about complex recombination reactions at surfaces. Information about surface conditions is largely inferred from measurements made on wafers after removal from the plasma and from beam-surface experiments used to simulate the plasma. Similarly, we are not able to control plasma processes because there are no guarantees that machines operate at the intended internal conditions: diagnostic techniques are needed to characterize both the plasma and wafer states *in situ* and in real time.

SURFACE PROCESSES

Surfaces exposed to plasmas experience bombardment by energetic ions, electrons, neutrals, and photons. The detail in which we understand the effects of such bombardment varies widely depending on the particular process. The goal of fundamental surface studies, both theoretical and experimental, should be to provide insight and data for process simulation and/or reactor design. Examples of the data needed are cross sections and rate constants for energy transfer, reaction, emission, surface diffusion, implantation, reflection, disordering, and recombination. All these processes affect material properties, and all are affected by exposure to the nonequilibrium, low-energy plasma.

Theory and Simulation

For physical sputtering and energy transfer, the most important properties of the projectile (ion or fast neutral) and target are their masses and their interaction potentials. This relative simplicity combined with a wealth of experimental data on sputtering has facilitated the development of sophisticated theories and simulation tools. For example, both rates and angular distributions of sputtered particles are empirically well established for monoenergetic rare-gas and metal ions incident on monatomic solids at energies above about 100 eV. For energies above 1 keV, measured neutral emitted fluxes are in reasonable agreement with results from numerical simulation codes. Indeed, the reliability of these codes has prompted their widespread use. More codes of this type are needed for plasma process simulation. However, few data are available for lower energies, molecular projectiles, or molecular targets. The reliability of these simulation codes is unknown for the conditions that are most pertinent to plasma processing.

First-principles simulations of plasma-surface chemistry have been relatively modest to date. Virtually no potential energy surfaces have been computed for relevant reactant-substrate interactions. A notable exception is the recent quantum-chemical calculation of the interaction potential for the fluorine-negative-ion and silicon interaction that helps explain extensive fluorine diffusion into the silicon lattice and the origin of doping effects on etching rates. However, the all-important effects of ion bombardment on surface chemistry have not been numerically simulated from first principles.

Simulations that account for the effects of microstructure are also sorely missing. In the etching of submicron features, for example, scattering of ions from the mask or substrate sidewalls and surface diffusion of species from sidewalls (Figure 4.2) might significantly alter the flux of ions and neutrals within the feature and thereby alter the etching rate and anisotropy. An understanding of the transfer of energy between surface and ion and the modification of the sidewall surface is needed to model the feature profile and to predict the dependence of etch and deposition rates on microstructure. Even less is known about the surface chemistry and physics at atmospheric pressure and high temperature (greater than 800°C), which are typical conditions for rapid deposition of diamond and superconducting films.

Recent progress in molecular dynamics simulations of gas-surface energy transfer processes, recrystallization, and surface reconstruction has been impressive. Extension of these techniques to simulation of low-energy ion implantation, ion mixing, impurity diffusion, nucleation, surface diffusion, and surface conduction, for example, would revolutionize our understanding of the plasma-surface interaction.

The understanding of electron emission from surfaces as the result of high-ionization-potential, low-velocity ions and metastable atoms approaching a surface has progressed very little since early work on rare gases in the 1950s. This work is applicable to ions with an ionization potential greater than twice the work function, so that many ions have too small an ionization potential for this model to be useful. Some recent studies for low-ionization-potential ions claim to have found a good correlation between the electronic stopping power of the ion and electron emission yields and a linear relation between yields and ion energy, for ion energies above a few kilovolts. The crucial question of the probability of electron escape and how it is affected by effects such as adsorbed gases has not been addressed for the low-ionization-potential projectiles. Ion-induced electron emission is very much an empirical science for clean surfaces and an art for most practical surfaces. First-principles theoretical calculations are available only for low-energy, high-ionization-potential rare gases on clean surfaces.

With the advent of massively parallel computing facilities in the next 5 to 10 years, simulations of surface processes like those discussed above should become increasingly easy to

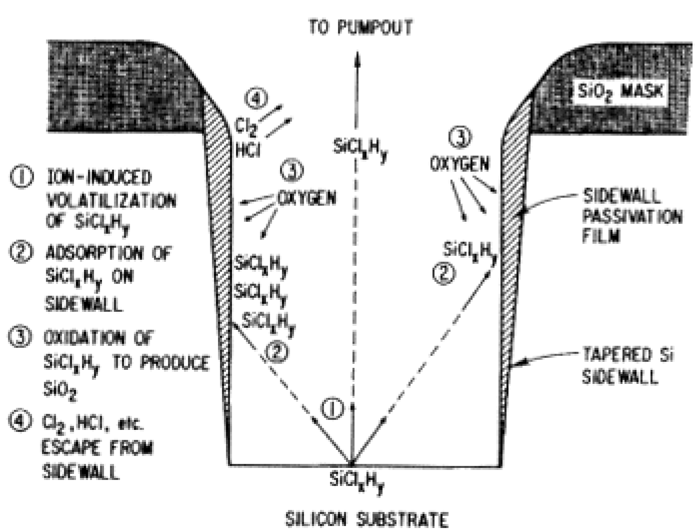

Figure 4.2
Model of the sidewall film formation mechanism for the plasma etching of silicon using various precursor gases. (Reprinted, by permission, from G. S. Oehrlein, J. F. Rebetski, and E. H. Payne, 1990, "Study of Sidewall Passivation and Microscopic Silicon Roughness Phenomena in Chlorine-Based Reactive Ion Etching of Silicon Trenches," J. Vac. Sci. Technol. B8, 1199. Copyright © 1990 by the American Institute of Physics.)

perform and increasingly more accurate. First-principles calculations of complicated chemical structures involving as many as 100 atoms per layer should be possible. Despite improvements in computational power, however, the panel expects that dynamic simulations will still be constrained mostly to simple systems and short interaction times. Experimental studies are crucial to ensure that the input to the computer programs is correct and to expand our understanding beyond what numerical approaches can offer.

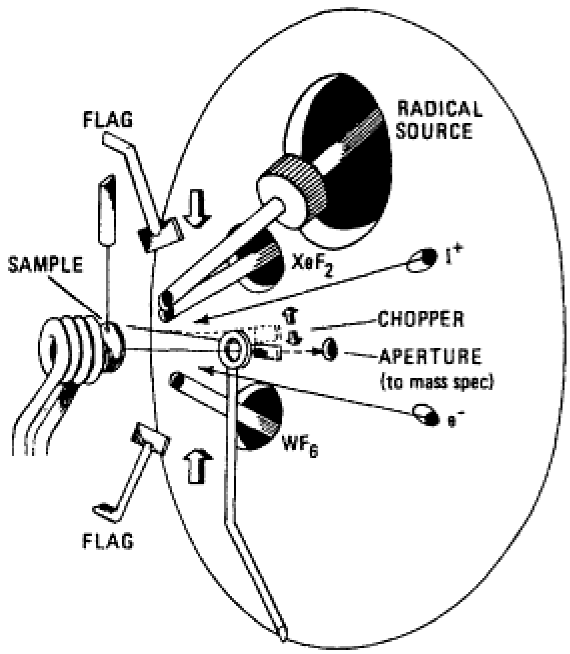

Figure 4.3
Schematic illustration of apparatus used for beam-surface experimental simulations of plasma etching and deposition. Such experiments are essential for developing mechanistic insight into plasma-surface interactions. (Reprinted, by permission, from H. F. Winters and I. C. Plumb, 1991, "Etching Reactions for Silicon with F atoms: Product Distributions and Ion Enhancement Mechanisms," J. Vac. Sci. Technol. B9, 197. Copyright © 1991 by the American Institute of Physics.)

Experimental Studies

Models of surface processes in plasmas are limited in part by lack of mechanistic insight and lack of kinetic data. The situation is similar to that in the field of surface science 25 years ago. At that time, neither the concentration of adsorbed species nor the surface structure could be determined, and there was little understanding of surface physics and chemistry. Since that time, many analytical tools have been invented or applied to the study of surface processes under well-controlled conditions. The ability to make these measurements has led to a much improved understanding of surface properties and surface chemistry. If appropriate tools and techniques are developed and brought to bear in a concerted fashion, similar strides in improving our understanding of etching, deposition, and cleaning processes should result.

Beam-Surface Experiments

Much of our fundamental understanding of surface processes occurring during etching and deposition comes from well-controlled plasma simulation experiments in which beams of ions, electrons, neutrals, and photons are directed either together or alternately at well-characterized surfaces (Figure 4.3). The beams are typically analyzed using mass spectrometry. The surface chemistry is usually diagnosed outside of the reactive environment by using conventional techniques such as x-ray photoelectron spectroscopy, Auger spectroscopy, ion scattering spectroscopy, and secondary ion mass spectrometry. Recently, analysis has also been performed *in situ* but under exceptionally low-pressure conditions. Reaction products desorbing from the surface as well as reflected reagents are also detected by mass spectrometry. Recent work at universities in the Netherlands has exploited the technique of laser-induced fluorescence to probe the internal energy states of reaction products.

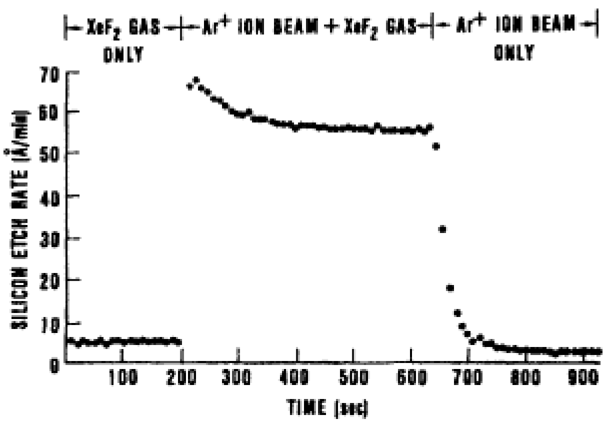

Figure 4.4
Etching rate of silicon as a function of time during sequential exposure to first a xenon difluoride molecular beam, then both a xenon difluoride and an argon ion beam, and finally just to an argon ion beam. The ion-neutral synergy is clearly evident—when both beams are on, the etch rate is much greater than the sum of the etch rates with either beam on alone. (Reprinted, by permission, from J. W. Coburn and H. F. Winters, 1979, "Ion and Electron Assisted Gas-Surface Chemistry—An Important Effect in Plasma Etching,"J. Appl. Phys. 50, 3189.)

Such experiments clearly demonstrated one of the most remarkable aspects of plasma etching: the synergy between ion bombardment and neutral chemistry that is prevalent in plasma etching and largely responsible for rapid, anisotropic etching. Figure 4.4 shows how the etching rate with both ion and reactive flux to the surface exceeds the sum of the individual etch rates for ion sputtering and neutral reaction. Without experiments of this type, we cannot hope to understand surface reactions that dominate the outcome of industrial plasma processes.

For fluorine etching of silicon, the synergistic role of ion bombardment is now well documented; but not all systems exhibit synergistic effects, and in some cases ion bombardment can even inhibit etching. Today, we still do not understand the microscopic mechanisms responsible for the ion-neutral synergy and cannot predict under which circumstances rate enhancement or rate inhibition will occur. The role, synergistic or otherwise, of energetic neutrals—formed by charge-transfer reactions with ions and by chemical reaction—in surface processes is also virtually unknown. Much work must be done to quantify synergistic effects so that predictive power is obtained and generalizations can be made. The most promising approach continues to be use of well-controlled, mass- and energy-selected ion and neutral beams directed at well-characterized surfaces.

The effects of surface topography and surface temperature are two other areas in which beam-surface experiments are needed to provide mechanistic insight and fundamental rate parameters. To date, studies have used only unpatterned thin films in etching studies; but the presence of microstructure and different materials, such as photoresist, on the surface is important in determining the outcomes of etching and deposition reactions. The recent pioneering work at Hitachi Central Research Laboratory on cryogenic plasma processing demonstrates the need for extending beam-surface interaction studies to the lower-temperature regime.

Beam-surface studies have been focused largely on etching reactions, but there is an even greater need for experimental simulation of plasma deposition processes. Consider the deposition of amorphous, hydrogenated silicon films. Although such films have been studied for many years, debate is ongoing concerning the dominant precursors to film growth. The pursuit of mechanistic insight has been hampered by the wide variety of plasma growth conditions and the correspondingly wide variety of film properties. Variations in atomic and molecular sticking probabilities during a film's growth inhibit quantitative analysis. The situation is even more muddled for diamond and diamond-like film deposition from methane and other hydrocarbon plasmas. With appropriate free radical and ion beams, sticking probabilities could be measured as a function of surface temperature, hydrogen surface coverage, and ion bombardment energy. Such studies would not only resolve controversies about deposition precursors but also help to determine optimal processing conditions for specific film properties such as crystallinity, photoconductivity, and thermal conductivity.

Beam-surface experiments are also well suited for determining the energy deposited by particles striking surfaces. This is a key parameter needed to understand and predict sputtering yields, etching rates, and film properties. How the energy is distributed and how much is deposited can influence the rates of reaction, the morphology of the surface, and the incorporation of impurities. Recent measurements of the energy transfer coefficients for rare-gas ions on metallic surfaces have provided better estimates of energy deposition for energies of interest between 1 eV and 4 keV. However, similar information is needed for composite surfaces and for a variety of ions, especially light ions such as hydrogen. Furthermore, the conventional assumption that molecules can be treated as an unbound group of atoms needs to be carefully examined, especially at incident energies comparable to the molecular binding energy.

Despite the insights gained in beam-surface studies, the approach has had significant limitations. First, fluxes of both charged and neutral particles are typically low relative to those found in plasmas. However, the ratio of these fluxes, frequently the important parameter, can easily be made equivalent. Although the advent of low-pressure, high-density plasmas is helping to narrow this "flux gap," we still need scaling relationships to connect beam-surface studies to plasma processes. Secondly, ion energies have generally been too large for comparison to the newest generations of plasma reactors. Because it is difficult to generate large fluxes of ions at energies below about 50 eV, the effects of ion bombardment at low energy are largely unexplored. Thirdly, and most importantly, appropriate sources for one-component, impurityfree radical beams have been lacking: a long-term commitment to radical source development would have a high payoff.

There are perhaps 20 to 30 groups in the world who have attempted to simulate plasma-surface reactions by using beam methods. Only a subset of these groups remain active today. The United States has pioneered this approach, but significant results have come from the Netherlands-owned Philips Corporation, universities in the Netherlands, laboratories in Germany, and chip manufacturers and universities in Japan.

These experiments are complicated and moderately expensive (requiring about $500,000 to $1 million in capital equipment), and much of the best work has been performed in a small subset of industrial laboratories. Nonetheless, this work can be carried out on a small scale with two or three principal investigators in university, national, or industrial laboratories.

Ex Situ Analysis

In recent years, plasma-treated surfaces have been transferred under high-vacuum conditions to surface analytical chambers. Although the fluxes, energies, and composition of particles impinging on the surface in the plasma may not have been controlled, much insight has been gained through such experimental work. For example, the large uptake of fluorine by silicon during plasma etching was shown to involve the formation of a relatively thick "selvedge" layer consisting of silicon fluorides of varying stoichiometry. This selvedge layer is an important factor in determining defect densities, defect diffusion, surface roughness, and etch rates with and without ion bombardment. Similar studies have been useful for understanding the effects of hydrogen plasmas on silicon substrates.

Recent angularly resolved experiments (Figure 4.5) have shown differences in the chemical composition of the sidewalls relative to the bottom surfaces of etched trenches. Such experiments are important in understanding the effects of redeposition and microstructure on etching processes (see Figure 4.2).

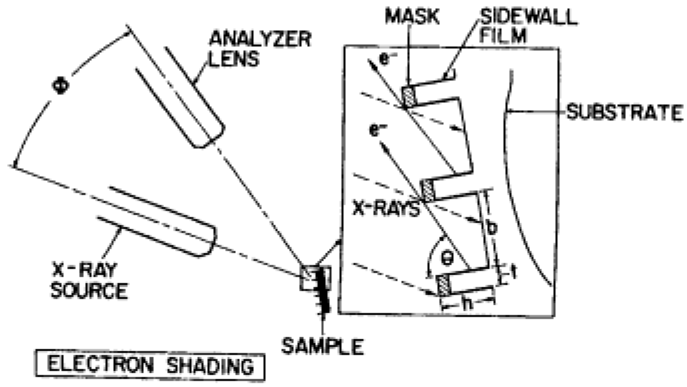

Figure 4.5
Schematic illustration of x-ray photoelectron spectrometer used to analyze sidewalls and bottom surfaces of plasma etched silicon trenches. (Reprinted, by permission, from G. S. Oehrlein, J. F. Rebetski, and E. H. Payne, 1990, "Study of Sidewall Passivation and Microscopic Silicon Roughness Phenomena in Chlorine-Based Reactive Ion Etching of Silicon Trenches," J. Vac. Sci. Technol. B8, 1199. Copyright © 1990 by the American institute of Physics.)

Because plasma reactors and surface analytical equipment are expensive, this research approach has been limited to a few industrial and national laboratories. The industrial laboratories involved are microelectronics manufacturers, not plasma reactor vendor companies, who develop both equipment and first-generation processes. In the United States, vendors generally lack resources for this kind of research, and chip manufacturers are only weakly coupled to the vendors. Japanese chip manufacturers, on the other hand, have exploited *ex situ* analysis in developing plasma etching and deposition processes in close collaboration with plasma reactor vendors.

Future plasma-surface work must make even greater use of in-vacuum transfer to analytical chambers if detailed understanding of the plasma process is to be obtained. This will be particularly critical to the development of plasma-based surface cleaning procedures. It will also be important to control the wafer temperature during the transfer to the analytical chamber if the mechanisms at play during cryogenic processing are to be properly elucidated. Such work requires collaboration between surface scientists and plasma process engineers and is an opportunity to exploit synergies between national, industrial, and university laboratories.

PLASMA GENERATION AND TRANSPORT

Large fluxes of energetic reactive particles—ions, electrons, neutrals, and photons—over large surface areas make plasmas useful in materials processing. Controlling reactive fluxes and energies is the key to controlling material properties and throughput. For example, the flux, energy, and angular distributions of the ions striking the surfaces are critical factors in determining rate, anisotropy, and damage during plasma etching. The densities and energy distributions of reactive particles that constitute the reactive fluxes in plasmas are, in turn, affected by numerous plasma parameters such as gas composition, excitation frequency, reactor geometry, reactor materials, electric and magnetic fields, pressure, and flow rate.

The nonlinear coupling between these plasma parameters, along with the propensity of discharges to function in a multitude of modes, has created formidable challenges for theorists and experimentalists alike. Nonetheless, rapid progress has been made in both modeling and experimentally characterizing plasma phenomena in the last decade. As a result, the coming decade should witness the advent of reliable tools for designing reactors (see Figure 4.1). Detailed, quantitative process simulation that includes chemical effects may take longer to develop, but basic studies that address process scaling over a wide range of parameter space, together with an increase in qualitative insight, are likely to enable an expert systems approach to process design and control in the near term.

Fundamental processes that govern reactive fluxes include dissociation, excitation, ionization, and recombination. Each of these can be mediated by electrons, ions, neutrals, or photons. In addition, electron attachment to make negative ions and ion-neutral charge transfer processes play important roles in influencing reactive fluxes to surfaces. While these gas-phase processes are generally well understood, a dearth of data prevents quantitative modeling of discharges. In the following sections, the panel addresses the approaches being used to develop simulation tools, the diagnostics needed to test them, and the basic data needed for quantitative prediction.

Low-Pressure Plasma Modeling

There are three types of models used today for low-pressure plasma processing discharges: analytic, fluid, and kinetic. These models differ in the degree to which a priori assumptions are made for quantities such as the form of the electron energy distribution function and the importance of particular transport processes. Kinetic simulations make the fewest assumptions and analytic models make the most; fluid models are intermediate. Conversely, kinetic simulations are the most computer intensive and analytic models are the least costly. Again, fluid models are intermediate. Each technique has its decided advantages. Analytic models are able to provide insight into the major physical processes at work and are robust and fast enough to provide valuable scaling laws. Fluid and kinetic models are able to represent complex geometries and address the details of individual reactors. Only kinetic models can provide accurate particle energy distributions that are so vital for plasma reactor design and process simulation. For process simulation, understanding the coupling between plasma chemistry and plasma physics is a critical challenge. For reactor design this coupling is not as limiting, and many tools being developed today may be applied in the near term to CAD.

When all three modeling approaches are brought to bear on the same problem, a great deal can be learned about discharge phenomena and about the strengths and weaknesses of each modeling approach. For example, in rf discharges, the mechanism for electron heating is important in determining the average electron energy and the shape of the electron energy distribution function. Both are critical parameters in determining the degree of ionization and dissociation and the magnitudes of the self-consistent electric fields that transport charged species to device wafers. Depending on process variables such as excitation frequency and power, the models tell us that electrons can be heated by stochastic collisions with the oscillating sheath, by ohmic heating in the plasma bulk, or by acceleration in the sheath electric field after secondary emission. The transition from bulk-dominated electron production and loss to electrodedominated electron loss has now been modeled by several groups using each of the three modeling approaches.

Analysis

Given the short time (approximately 10 years) and few resources that have been devoted to plasma process modeling, significant progress has been made. However, only a few predictive analytical models exist for even the simplest, planar reactive ion etchers. These are one-dimensional, self-consistent models that assume a separation of the discharge into a quasineutral plasma "glow" region surrounded by nonneutral sheaths (see Figure 3.11). Equations used in glow and sheath regions are connected to describe the electron and ion particle, momentum, and energy balance. Coupled with Poisson's equation to determine the electric field, the models describe the self-consistent discharge state and the scaling of discharge parameters such as plasma density, electron temperature, ion energy, and ion flux as process variables such as rf frequency and power, gas pressure, and electrode spacing are varied. By and large, few such models deal with chemically interesting discharges. The effects of free radicals, negative ions, and multiple positive ions are rarely modeled.

The analytical modeling of magnetically enhanced discharges, such as ECRs and planar magnetrons, is at an even earlier stage of development. Only zero-dimensional (no spatial variation) self-consistent models have been developed. As a simple example, there is no self-consistent model to determine the radial and axial uniformity of a plasma injected into a magnetic bucket process chamber.

Many examples show how plasma theory has had a direct impact on the design of new controlled-fusion reactor configurations. The theoretical capability has yet to be developed and exploited in plasma processing, primarily because very little basic research has been devoted to processing.

Fluid Simulations

One approach to dealing with the complexity of processing discharges is by means of fluid simulations, in which each of the charged particle species (electrons, and positive and negative ions) is treated as a separate fluid, characterized by its temporally and spatially varying density, average velocity, and average energy. It is not necessary to arbitrarily divide the discharge into glow and sheath regions, as is done in most analytical models. However, a fundamental assumption is made that the particle distribution functions of the various species are known; *e.g.,* they are usually taken to be drifting Maxwellians. In some cases, one separates a given species (generally electrons) into two or more groups, each with its own density, velocity, and energy.

The fluid approach has been most successfully applied to simulating the behavior of materials processing discharges at pressures above about 100 mTorr, where transport is collision-dominated and particle distribution functions are near-Maxwellian. Although some two-dimensional work has been done, most efforts have led to one-dimensional simulations of RIE discharges, using model gases with negative ions and simple surface interaction coefficients. Complicated chemistry and neutral particle fluid dynamics have not been generally included. These approaches are more powerful than they might seem because they incorporate all conservation laws. Although quantitative comparisons with experiments are lacking, qualitative agreement between theory and experiment has been remarkably good.

There is little doubt that two-dimensional simulations of RIE and magnetically enhanced discharges that incorporate more detailed chemistry and surface science will lead to increased understanding of higher-pressure processing plasmas, such as those used in deposition. But the trend toward lower pressures for etching suggests that the fluid approach may have fundamental limitations in describing the next generation of etching reactors. In general, average velocity and energy will not suffice, and calculation of the distribution functions will be required for accurate simulation of reactors and processes.

Fluid simulations for materials processing lag far behind those for controlled-fusion research, in which three-dimensional simulations on multitasked, vectorized supercomputers are common. The first self-consistent fluid simulations of rf parallel plate discharges were performed only in the mid-1980s at the University of Minnesota. Since then, there has been dramatic progress at a relatively small number of U.S. universities. There are comparably strong efforts in France and, recently, similar work has been begun at Japanese universities.

Particle-In-Cell and Kinetic Simulations

The most fundamental simulation approach is that based on particle-in-cell (PIC) techniques coupled with Monte Carlo collisions, or that based directly on integration of the Boltzmann equations for each of the discharge species. In the PIC technique, the plasma is represented as a set of superparticles. The Lorentz force on each superparticle determines its self-consistent motion, and the charges and currents generated by the moving, charged superparticles determine the self-consistent fields through Maxwell's equations. Monte Carlo techniques are used to determine the short-range collisional processes (ionization, scattering, and so on) that occur during the simulation. A different technique that has similar capabilities is direct integration of the Boltzmann equations with the proper collisional terms for each species. Both approaches yield time- and space-resolved information on the charged particle velocity distribution functions in a discharge from which fluxes and generation rates can be calculated.

The convective scheme (CS) is a method for kinetic simulations that, like the PIC technique, advances particles during each time step. However, the CS method redistributes the particles after each time step on a phase space mesh. This eliminates the need for Monte Carlo collisions and eliminates statistical noise.

Although they are quite complete, these simulations are time intensive. Present models use simplified sets of cross sections (*e.g.,* ionization, scattering, and charge transfer in argon) and estimated surface emission coefficients to treat up to three charged species (electrons, and positive and negative ions) in one-dimensional geometries. These models have led to greatly increased understanding of energy deposition and other physical processes in RIE discharges and serve to certify some assumptions made in both fluid simulation and analytical modeling. There have been few quantitative comparisons of PIC, CS, or Boltzmann simulation results with experiments, although there is evidence that some phenomena seen in particle simulations have been identified in experiments.

Particle simulation of processing discharges lags far behind that done for controlled-fusion reactors. The application of kinetic simulations to processing discharges started almost simultaneously in the United States and in Australia. Only a small number of groups are currently using this method, but that is likely to change in the near future. Monte Carlo simulations of plasma transport are widespread in the United States, Europe, and Japan, but there have been few attempts to include self-consistently calculated fields.

Thermal Plasma Modeling

Numerical models of thermal plasmas have been developed for free-burning arcs, wallstabilized arcs, and convection-stabilized arcs. More recently, arcs with turbulent boundary layers in high-velocity nozzle flows have been extensively characterized through models and diagnostics. Similarly, considerable advances have been made in the predictive description of induction plasmas. Nonuniformities caused by asymmetric cooling or by cold gas injection have been investigated, as have deviations from local thermodynamic equilibrium (LTE) due to strong temperature and density gradients. Both composition nonequilibrium due to chemical de-mixing and electron-heavy particle energy nonequilibrium have been described quantitatively. Considerable work has been done describing radiative transport, including partial self-absorption for simple geometries.

Modeling of turbulent plasma jets is a precondition to a detailed and predictive understanding of the plasma spray process. In other materials processing applications, such as metallurgical refining or reclamation or waste processing, turbulent plasma jets are also used. Most modeling of such jets has been with various forms of a two-dimensional model that describes the turbulence in terms of kinetic energy dissipation and velocity variation, *i.e.,* a κ-ϵ model. Advances have been made by using a low-Reynolds-number approach. Time-averaged velocity and temperature distributions agree well with time-averaged measurements. However, average quantities are insufficient to fully describe the plasma spray conditions. Large-scale turbulent fluctuations (Figure 4.6), cold gas entrainment, and three-dimensional effects must be considered. New approaches are needed for the description of large-scale turbulence. Even with the most advanced supercomputers, it will be impossible for many years to come to calculate the turbulent flows on a purely deterministic base. Advances that are being made in the modeling of isothermal jets should be investigated to see if they could be applied to the plasma jets with strong temperature, velocity, and property gradients.

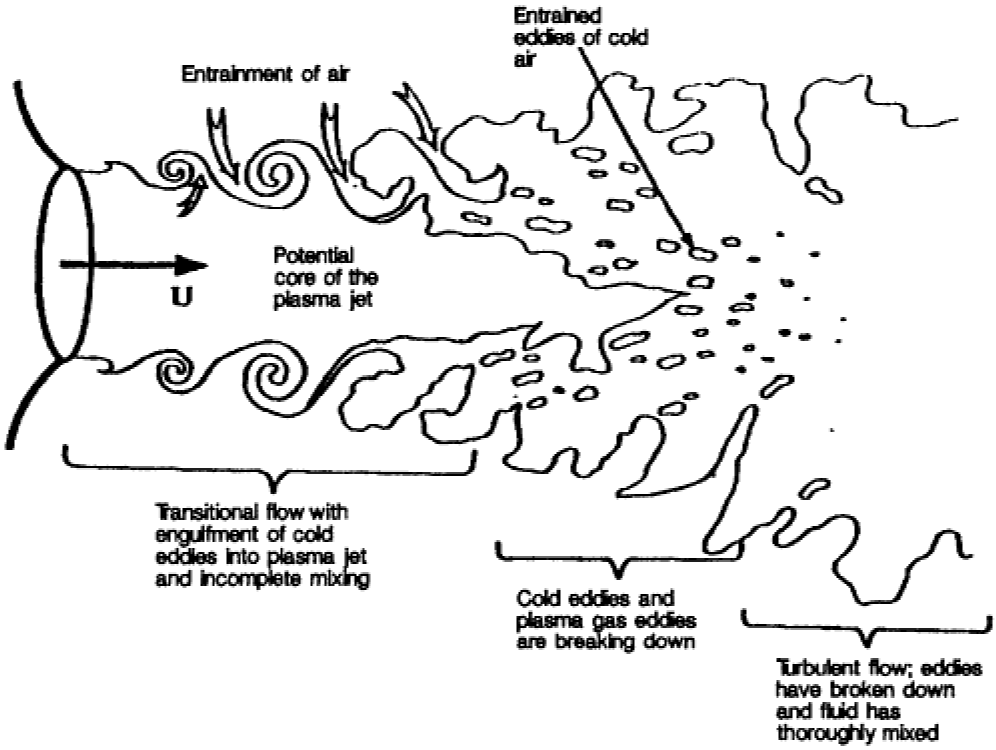

Figure 4.6
Schematic illustration of turbulent plasma jet and resultant complexities that challenge scientific understanding and limit technological applications. (Reprinted, by permission, from E. Pfender, W. L. T. Chen, and R. Spores, "A New Look at the Thermal and Gas Dynamic Characteristics of a Plasma Jet," Proceedings of the Third National Thermal Spray Conference, Long Beach, Calif., May 1990.

Thermal plasmas used for materials processing are usually inhomogeneous with regard to substance and phase, *i.e*., particulates or droplets in a vapor environment, and gas mixtures whose compositions vary strongly with position. Energy exchange and momentum exchange in multiphase mixtures have been described; however, the results are strongly dependent on the simplifying assumptions made. Values for thermodynamic and transport properties remain a point of contention, particularly when strong gradients and gas mixtures are encountered. Occasionally, the choice of suitable values provides the degree of freedom necessary to match modeling results with experimental data.

Most thermal plasma models and diagnostic studies have used simplified plasma geometries and restricted parameter sets. Since plasma parameters are strongly interdependent, neglect of one parameter may severely limit the validity of the results. For example, it is easily seen that a slight constriction of a 100-A arc generates negligible magnetic pinch forces; however, these forces may result in the influx of cold gas and stronger cooling of the arc, thus forcing a stronger constriction and possibly an instability. Neglect of the pinch effect will, therefore, not give the correct prediction. The consequence of these simplifications is that our predictive capability exists only within a limited parameter range that may not be pertinent to applications. In general, we are unable to scale plasma systems to higher powers.

Toward Cad Tools And Expert Systems

Kinetic descriptions for electrons, ions, and neutrals in materials processing plasmas are required for modeling both gas-phase and surface chemistry and understanding the effects of complex reactor geometry. Hybrid models that combine analytical, fluid, and kinetic approaches are likely to be effective for use in CAD tools and expert systems. In this way, both the accuracy provided by the kinetically derived distribution functions and the speed provided by fluid and analytical methods can be exploited. For example, kinetic simulations could be performed first for a simplified geometry to test assumptions in fluid and analytical models. These models could then be used in an expert system to provide guidance for scaling processes. A more sophisticated approach appropriate for computer-aided design of reactors has already been explored. A fluid simulation is first used to calculate approximate densities, energies, and fields. The fields are then fed into a PIC code to compute distribution functions whose moments are then used iteratively to refine the fluid equations. Process variables can be changed and a new set of distribution functions, fields, and fluxes computed rapidly. With additional resources, this approach could be used to evaluate different geometric and electromagnetic reactor designs. Even without the data on gas-phase and surface processes necessary for quantitative calculations, meaningful comparisons between designs could be made and the sensitivity of the model (and reactor) to the unknown data determined.

Chemical Kinetics

A major challenge for process expert systems will be to incorporate chemistry into the electron and ion transport models. Currently, gas-phase chemistry is added after the basic discharge parameters have been "determined." A common approach is to assume a specific "known" electron density and temperature. The chemistry is then modeled, either using zero-dimensional rate equations for the various neutral species, with rate constants based on the "known" plasma conditions, or using one-dimensional or multidimensional diffusive, free-flow, or Monte Carlo transport models for the generation and loss of neutral species. Closing this open loop to solve simultaneously for both charged and neutral particle concentrations and energy distributions is a prerequisite for successful process simulation. With sufficient computational resources and a reliable data base, incorporating chemical kinetics into the simulations will not be difficult. The challenge will be to select the critical reactions and ignore the rest.

Multidimensional Modeling and Magnetic Effects

The models need to embrace two- and three-dimensional effects important for determining ion bombardment energies and uniformity across large surfaces. Problem areas include the distribution of current to numerous surfaces, the effects of nonuniform magnetic fields, magnetic field lines intersecting electrodes and insulating surfaces, and the effects of sheaths and double layers. To date, magnetic enhancement has been incorporated only in the simplest manner, and more sophisticated models must be developed.

Stability of Processing Plasmas

Understanding or at least obtaining empirical descriptions of the stability of plasmas is essential to the control of processing plasmas. Low-pressure plasmas also have a tendency to operate in different modes (Figure 4.7) that could help to explain anomalous process results. The stability properties of rf and, especially, dc discharges are poorly documented, although the consensus is that rf discharges are more stable when operating in the bulk electron heating mode. Discharge mode changes and/or oscillations are known to occur in microwave-driven plasmas at higher pressures, in magnetron configurations at high currents, and in situations where sheath voltages and currents are large. Plasma reactor design can play a determining role in mode changes as current paths switch from surface to surface. Theory can provide much needed understanding of such instabilities.

The stability of thermal plasmas has been a long-standing issue. The issue of turbulence in thermal plasma processing has already been discussed above ("Thermal Plasma Modeling") and identified as a major issue. Arc discharges are inherently unstable and often display several magnetohydrodynamic (MHD) instabilities. However, quantitative descriptions of several of these instabilities exist, and designs for stabilizing the discharge are used routinely. Unfortunately, our understanding is significantly less complete for instabilities encountered in thermal plasma jets, or in interface regions between plasmas and surfaces.

Accuracy and Reliability of Numerical Simulation Methods

Comparing the results of simulation with those of well-characterized experiments and with other simulations is crucial for the development of CAD tools and expert systems. Such comparisons clarify nonphysical assumptions and identify key physics and chemistry that must be incorporated. A reference reactor problem should be defined to facilitate comparisons between codes. By applying each code to the same problem, the relative accuracy and efficiency of the simulation method can be evaluated.

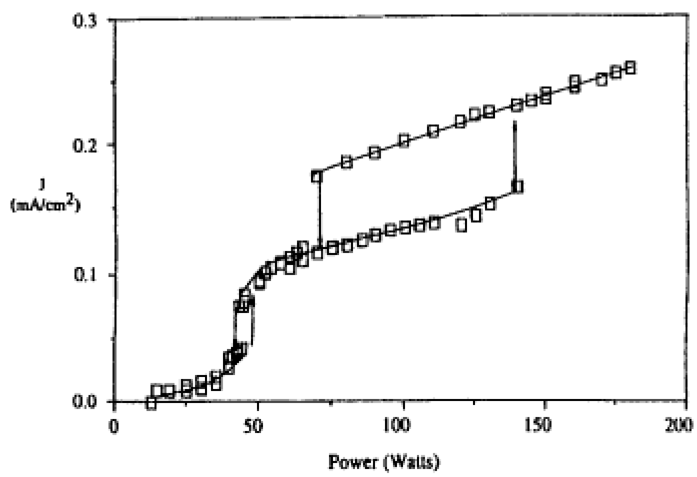

Figure 4.7
Current density as a function of power in a radio-frequency discharge through chlorine illustrating two stable states and regions of instability. (Reprinted, by permission, from E. S. Aydil and D. J. Economou, 1991, "Multiple Steady States in a Radio Frequency Chlorine Glow Discharge," J. Appl. Phys. 69, 109. Copyright © 1991 by the American Institute of Physics.)

Plasma Diagnostics

To test the validity of plasma models, measurements of particle densities, fluxes, and energy distributions are vital. Along with the electric fields that control charged-particle transport, these parameters determine how the plasma affects material properties. Although what impacts the surface is of ultimate interest, to control this bombardment we must consider the entire discharge as well as its bounding surfaces.

Despite significant advances in diagnostic capability in the last decade, *quantitative* comparisons between experimental groups and between experimental and theoretical groups have been noticeably absent. This is partly the result of a plethora of reactor configurations and "conditioning" recipes. By using reference reactors (see below), the development of new quantitative diagnostic tools will be expedited and more complete diagnostic data sets will be assembled for rigorous testing of plasma simulations.

These experiments are simpler and less expensive than their surface analytical counterparts and, as a result, many small groups of researchers have obtained a wealth of information. The United States has played a major role in the development and application of diagnostic techniques to plasma processing. The research has been performed at industrial, national, and university laboratories. But comparable efforts have also been established in Europe—in France, Germany, England, and Italy primarily—and more in Japan. While the efforts in the United States have been largely uncoordinated and lack the participation of plasma reactor vendors, both Japan and France have national programs in reactive plasma diagnostics and simulations (discussed below in the section titled "Funding for Plasma Processing Research").

Positive Ions and Neutrals

To interpret and apply beam-surface and sputtering data for monoenergetic ions to plasma processing, we need to know the flux, energy, and angular distributions of ions and neutrals incident on the surface. Mass spectrometric and optical techniques are the most reasonable approaches for measuring these quantities.

The value of mass spectrometry resides mostly in its versatility. All heavy-particle species, in principle, can be extracted from the plasma and mass analyzed. Electrostatic grids or a hemispherical magnet are but two schemes commonly employed for energy analysis. There are, however, several problems. First, these methods are inherently intrusive; *i.e.*, the plasma parameters to be measured are distorted by the measurement process. With proper care, these effects can be minimized, but they must always be considered in the data analysis. Secondly, it is difficult to separate fragments generated in the mass spectrometer ion source from radicals arriving from the plasma. However, this problem can be solved by sampling the plasma using modulated-beam mass spectrometry and time-of-flight analysis: the fragments generated in the ionizer are not modulated as are particles of the same mass arriving from the plasma. Mass spectrometric sampling also suffers from poor angular resolution, although through careful experimental design of the sampling orifice and the electrostatic lenses, ion angular distributions can be estimated.

The heavy-particle velocity distribution function can be obtained directly from the Doppler broadening of either emission or laser-pumped fluorescent lines. Doppler-shifted laser-induced fluorescence (LIF) has been used successfully to measure translational velocity distributions of both ions and neutrals in plasmas. This method is nonintrusive and provides high three-dimensional spatial resolution but is often not useful for high-density plasmas when Stark broadening dominates the line shape. In addition, LIF suffers from a lack of generality—only certain atoms and molecules can be detected with sufficient sensitivity. An alternative method that does not suffer from these problems but lacks sensitivity is Doppler-shifted elastic (Rayleigh) light scattering. This method has been used in diagnosing high-pressure arcs and flames.

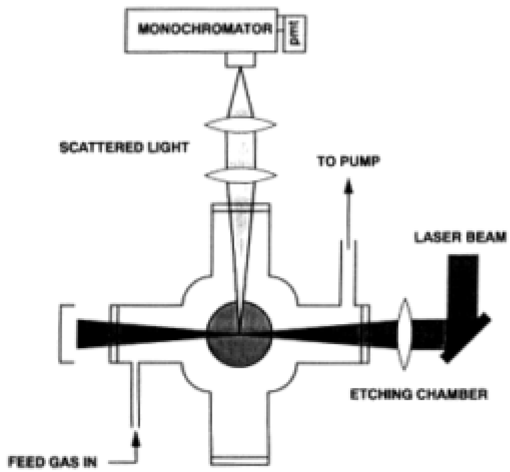

Figure 4.8
Schematic illustration of apparatus used for laser light scattering diagnostics such as laser-induced fluorescence and particle monitoring. (Adapted, by permission, from G. Selwyn, J. Singh, and R. S. Bennett, 1989, "Rastered Laser Light Scattering Studies During Plasma Processing: Particle Contamination Trapping Phenomenon,' *J. Vac. Sci. Technol*. A9, 2817. Copyright © 1989 by the American Institute of Physics.)

For heavy particles impacting surfaces, mass spectrometry remains the only viable technique; optical methods are not applicable because of vignetting by the electrode surface. Processes such as charge transfer are important in determining the energy of the ions and the flux and energy of fast neutrals reaching the surface, but there are few data for the large number of gaseous mixtures used in plasma processing. Information on collisional dissociation for many of the molecules of interest is especially lacking. Similarly, essentially no data are available for modeling the angular scattering of the many different ions and fast neutrals reaching the plasma-surface interface.

Most of our knowledge, albeit qualitative, of the plasma state has come from optical emission spectroscopy. Optical emission is useful for determining the presence of certain atoms or molecules and under some circumstances can be normalized to emission from an inert species (actinometry) to estimate relative, ground-state densities and qualitative changes in the electron energy distribution function. Emission can also be used in measuring the internal energy distribution functions of molecules—electronic, vibrational, and rotational. However, with optical emission, numerical transformation of the data must be performed to obtain fully spatially resolved distribution functions and densities; this requires extraordinary signal-to-noise ratios and is not generally practiced in diagnosing processing discharges.

Where feasible, laser light scattering (Figure 4.8) is preferred over optical emission spectroscopy because it offers high, three-dimensional spatial resolution. On the other hand, quantitative interpretation of LIF data is limited by the availability of radiative transition probabilities and collisional quenching rate constants. This situation can be alleviated by operating under optical saturation conditions, although problems associated with the size and shape of the volume probed and concerns over the approach to steady-state populations during short-pulse excitation cause interpretational problems. In general, it is necessary to calibrate the LIF experiment using other techniques, such as chemical titration. Nonetheless, the technique is valuable in determining relative changes in densities and energy distribution functions.

Using either optical or mass spectrometric techniques, effective, *in situ* rate coefficients can be determined by modulating the plasma power (or some other process variable) and monitoring changes in ion and neutral densities as a function of time. Both gas-phase and surface reaction rate coefficients have been determined by this method, but this approach has not been fully exploited in providing both input and tests for plasma simulations. Time-resolved light scattering could also be useful for characterizing plasma turbulence and instabilities.

Optical and infrared absorption spectroscopy are two other techniques that have been used to measure both densities and internal energy distributions in plasmas. Although more versatile than emission or fluorescence, especially when applied in the infrared, the techniques suffer from line-integrated detection and poor sensitivity. Nonetheless, reliable quantitative information has been obtained, for example, on radical concentrations and dissociation in silane plasmas used for amorphous and polycrystalline deposition of silicon. With additional support, these techniques could be much more widely applied.

Coherent Anti-Stokes Raman Spectroscopy (CARS) has been widely used in diagnosing combustion processes and in a few instances thermal plasma reactors. What the method lacks in sensitivity, it makes up for in generality, and it is most useful for detecting majority species. The CARS signal appears as a laser-like coherent beam for high collection efficiency, excellent fluorescence and luminosity discrimination, and high spatial and temporal resolution. Along with spontaneous and stimulated Raman spectroscopy in lower-pressure discharges, CARS is useful for determining degrees of molecular dissociation and gas density gradients as well as internal energy distributions. When a broadband source is used, the entire CARS spectrum can be generated simultaneously on the time scale of a single laser pulse. This approach should prove invaluable in providing data on turbulence and instabilities in the coming decade.

Electron Density and Energy Distribution

Despite problems of intrusion, contamination, rf interference, and interpretation, the most widely used plasma diagnostic is the electrostatic probe. Each of these problems can be overcome at least partially, and probes provide useful estimates for electron and ion densities and the electron energy distribution function. For electron density measurements, calibration is possible using microwave interferometry. Similarly, for ion densities, the techniques discussed above can, under favorable circumstances, be used for calibration. In high-density, thermal plasmas, Thompson scattering can be used to make both electron density and energy distribution measurements; but, for the lower-density discharges most often used in electronics materials processing, the electrostatic probe is the only method available. When properly applied, probes offer valuable insights into discharge phenomena. For example, careful probe measurements have been used to test theories of rf electron heating and to distinguish between different modes of excitation. This is a well-developed diagnostic technique that is easily implemented in small-scale experimental work. The greatest challenge will be dissemination of information on probe construction and measurement techniques and continuing education on their proper use.

Fields

To fully understand charged-particle transport and modes of electron heating in plasmas, we need to measure electric fields both in the bulk plasma and in the sheath between the plasma and the surfaces. In high-current arcs, such as those used in metallurgical processing, and in resonantly excited low-pressure plasmas it may also be necessary to measure both time-dependent and dc magnetic fields. For electric fields, there are now a variety of techniques ranging from electron beam deflection and Langmuir probes to LIF and laser optogalvanic spectroscopy. While rapid progress has been made, challenges remain in making field measurements with adequate time resolution and sensitivity for studying rf and microwave discharges, instabilities, and turbulence.

Negative Ions

Negative iota often occur in processing discharges. Both mass spectrometric and optical methods have been employed in their detection, but neither approach has offered sufficient detail. Mass spectrometric analysis is hampered by the trapping of negative iota in the plasma;

it is difficult to extract them without significantly perturbing the plasma. Optical techniques such as photodetachment are difficult to make quantitative without using auxiliary probes that can be intrusive or microwaves that lack spatial resolution. To date, negative-ion energy distributions have escaped characterization completely.

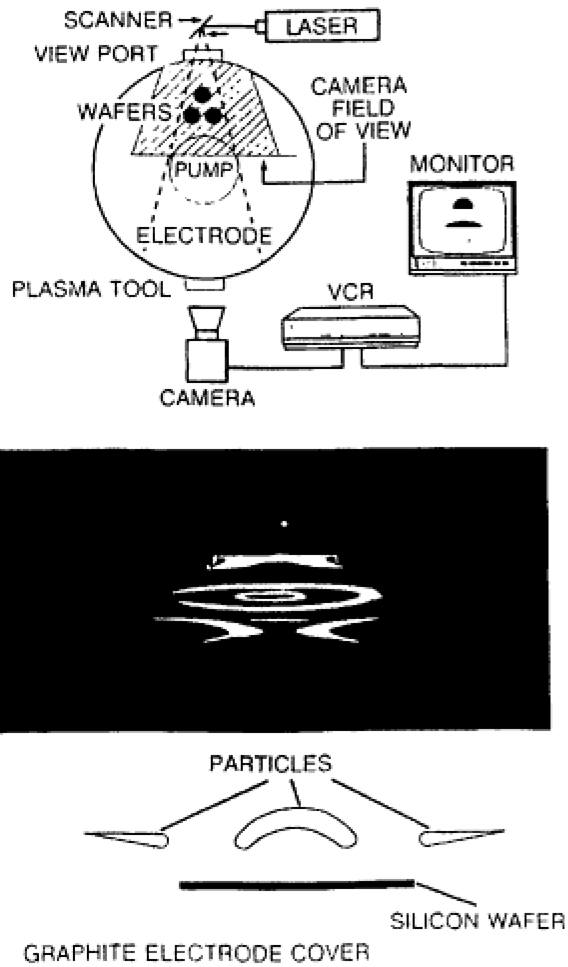

Figure 4.9
Light scattering apparatus used to monitor particulates above three wafers in a parallel-plate discharge (top); corresponding light scattering signal recorded using a video camera (middle); and schematic illustration showing where particles congregate above and near wafers (bottom). (Reprinted, by permission, from G. S. Selwyn, J. E. Heidenreich, and K. L. Hailer, 1990, "Particle Trapping Phenomena in Radio-Frequency Plasmas," Appl. Phys. Lett. 57, 1876. Copyright© 1990 by the American Institute of Physics.)

Until recently, conventional wisdom suggested that negative ions were nothing more than a curious anomaly of processing discharges and had little effect on material properties. But it is clear that negative ions have dramatic effects on discharge properties, on interpretation of probe diagnostics, and on material properties. For example, large concentrations of negative ions result in large bulk electric fields that modify both positive-ion and electron energy distribution functions so that they differ from what they would be without negative ions. Perhaps most importantly, negative-ion kinetics may play a major role in the formation, trapping, and transport of contaminating particulates in discharges.

Particulates

The prevalence of particulates in low-pressure processing discharges has recently been recognized. Many questions remain concerning formation, loss, and transport mechanisms. Light scattering has been the primary experimental diagnostic tool (Figure 4.9; see also Figure 4.8), but extraction of both size and density distributions has been largely absent. In particular, particles smaller than 0.1 micrometer will become increasingly important as integrated circuit device dimensions shrink, but light scattering does not appear to be sufficiently sensitive for such small particles.

Reference Reactors

Difficulties in comparing experimental results between laboratories and with theory are aggravated by the wide number of reactor configurations and "conditioning" procedures in use. To address this problem, the reference reactor concept was born and a fledgling effort has begun. The reference reactor is designed to:

- Provide a common platform on which experimental measurements can be rigorously and quantitatively compared. Meaningful comparisons between different research groups will be possible.
- Provide a test bed for new and old diagnostic techniques. By having identical reactors around the country, new diagnostic results can be rapidly reproduced. An experimentalist trying to learn a well-established technique, such as electrostatic probes, will have a wealth of diagnostic data with which to compare his or her results.
- Provide an exhaustive data set of plasma parameters in a relatively simple discharge system against which theoretical predictions can be tested.

The reactor should be a reference system and, as such, inexpensive and simple to construct.

An initial reference reactor effort has been begun by informal collaboration between Sandia National Laboratories, AT&T Bell Laboratories, Wright Aeronautical Laboratory, IBM, the University of New Mexico, the University of Michigan, and the National Institute of Standards and Technology. The parallel-plate, rf reactor was designed at Sandia National Laboratories and is referred to as the GEC Reference Cell; the name is derived from the 1988 and 1989 gaseous electronics conferences at which the reference reactor concept was conceived. After receiving identical cells, each of the laboratories has made nominally identical measurements of current, voltage, and power, and the preliminary design is now under review.

The reference reactor can be an effective means for making rapid progress in instrumentation, simulation, and understanding. The current effort is a good example of how industrial, government, and university laboratories can collaborate effectively. To the best of the panel's knowledge, similar reference experiments on thermal plasmas or high-density, magnetized plasmas are not being planned. However, such programs would appear to have high merit.

Data Base for Plasma Generation and Transport

Although many of the necessary experimental and theoretical tools exist now or will exist in the near future, the basic data needed both to model and to diagnose plasma processes are generally lacking or are at best difficult to access. These data base limitations are impeding progress in plasma process simulation and reactor design.

Basic data for gas-phase reactions are the essential underpinning for analytical modeling, computer simulation, and experimental measurements of plasma-assisted materials processing. At the most fundamental level in the gas phase, basic data comprise energy- and angular-dependent cross sections for electron-ion, electron-neutral, ion-neutral, and neutral-neutral collisions. Collisions of photons with heavy particles are also of interest. Data such as transport coefficients and reaction rate coefficients (integrated over specified energy and angular distributions) are also important.

Present Status

Significant progress has been made in generating data bases for noble gases and diatomic gases such as hydrogen, nitrogen, and oxygen. This progress has been spurred by applications to fusion and atmospheric modeling. Recently, important scientific problems, such as atmospheric ozone depletion, have led to cross section and rate coefficient compilations for the chlorofluorocarbons. For any gas, no matter how simple, it is imperative to work with cross section *sets* that use all available information. But, for plasma processing of electronic materials, gaping holes in the data base exist. For example, the cross section set for CF_4/oxygen discharges, used in silicon and silicon dioxide etching, is incomplete. The situation is even worse for newer etch chemistries, such as those involving bromine-containing gases, and for deposition processes. For example, silane and tetraethoxysilane are used extensively in silicon and silicon dioxide PECVD, respectively, but cross sections for electron impact fragmentation into reactive species such as $Sill_x$ (x= 1,2,3) and $Si(OH)_x$ (x= 1,2,3,4) have been neither measured nor calculated.

The experimental methods used to generate the existing data base are mostly well established. Crossed beams or beam-gas systems of molecules, atoms, electrons, and ions are useful for making energy-dependent cross-section measurements. Swarm and drift-tube measurements have been used for many years in the determination of rate constants as a function of temperature. Recently, progress has been made in measuring electron-impact ionization and fragmentation cross sections for free radicals and metastable states. Similarly, methods to measure dissociation cross sections and the yields of neutral products have been developed. But progress in generating data bases suffers severely from lack of funding and lack of coordination with modeling and diagnostic efforts.

The coming of age of massively parallel computers can revolutionize the calculation of electronic, ionic, and heavy-atom cross sections for complicated, chemically reactive systems. The development of standard cross-section codes, along with a judicious program of measurements to verify the calculation, would have an enormous impact on the understanding and design of systems for the plasma processing of materials.

Needs

Electron-heavy particle impact collisions are central to modeling, simulation, and experiments. Noble-gas discharges are maintained by electron-neutral ionization, and energy balance is determined in part by ohmic heating and collisional electron energy losses such as ionization, excitation, and elastic scattering. For diatomic gases, electron-impact vibrational and rotational excitations also contribute to energy loss. In molecular gases, electron-impact dissociation is the driving force behind much of the chemistry; it is also an electron-energy-loss mechanism that can inject several electron volts into ionic and molecular fragments. Because negative ions tend to be electrostatically trapped in discharges, electron impact detachment processes are important in halogen- and oxygen-containing discharges. Electron-positive ion recombination can be an important charged-particle-loss mechanism at high charge density. For plasma deposition of new materials, we need data on organometallic systems and on metals and their oxides, carbides, and so on.

Heavy-heavy particle-impact collisions (ion-neutral and neutral-neutral) are primarily important at higher gas pressures, such as those used in deposition and thermal plasma spraying, but they also play a critical role in determining the angular distribution of ions at surfaces. For low-pressure plasma etching, for example, ion-neutral collisions in the sheath may be very important in determining the extent of linewidth loss and how etching rates depend on aspect ratio. At pressures as low as 1 mTorr, resonant charge transfer and elastic scattering are both important in general. Because negative ions are trapped, negative ion-neutral detachment processes can be important along with ion-ion recombination in determining negative ion loss and thereby the magnitudes of electric fields and negative particulate trapping.

Optical diagnostics such as laser-induced fluorescence make use of specific atomic or molecular levels, and therefore, cross sections for collisions with excited states and for radiative transitions are central to the measurement and modeling of discharge behavior.

The materials processing community needs to establish a consensus on its critical data needs. Using process simulators, key cross sections and cross-section sets can be more easily identified. Providing that a mechanism exists for cross-section measurement, the needed data can be generated relatively quickly. The effort made in generating data for atmospheric modeling is a good example of what could be done for plasma processing.

Distribution of Information

A major difficulty confronting modelers and experimentalists is to assemble the basic data set appropriate to their application. Although some measured or calculated basic data exist for chemically complex discharges, it is often difficult to find these data and evaluate their reliability. Further, data sets are mostly incomplete, and therefore simple analytical estimates or semiempirical relations must be applied. The procedures for doing this are not well known.

The scientific literature is the primary source for measured and calculated cross sections, transport coefficients, reaction rate constants, and plasma-surface interaction coefficients. Bibliographic references to this vast literature include files of atomic and molecular processes compiled at the Oak Ridge National Laboratories, the Joint Institute for Laboratory Astrophysics, the Laboratory de Physique des Gaz et des Plasmas (France), the Queen's University of Belfast (United Kingdom), the National Institute of Standards and Technology, the Institute of Plasma Physics, Nagoya University (Japan), the Kurchatov Institute of Atomic Energy, Moscow (USSR), and the International Atomic Energy Agency, Vienna (Austria).

Analytical estimates, empirical formulas, and scaling from known to chemically unknown systems are generally required to complete a data set. This information is available in the scientific literature and is summarized in numerous textbooks and research monographs. However, complete cross-section sets for a given material system are generally not easily found or generated; yet, such sets are essential input to a plasma process simulation or reactor design.

PLASMA-SURFACE INTERACTIONS

The panel has discussed the status of surface and plasma research as it pertains to plasma processing, but the interactions between plasma and surface are the essence of materials applications. A combination of measurement, model, and simulation will be needed to parameterize algorithms with respect to such hard-to-control or ill-defined variables as secondary emission coefficients and sticking probabilities. The goal is not just to calculate plasma generation and transport but to relate them to wafer material properties. The wafer material properties, on the other hand, will affect charging and emission and thereby generation and transport of plasma.

Surface interactions with thermal plasmas are characterized by a boundary layer between the sheath and the plasma in which extreme density and temperature gradients exist. These gradients dominate the mass and energy transport and give rise to strong deviations from LTE.

Boundary Conditions

The properties of surfaces cannot be divorced from plasma simulation or experiment. Surface properties determine boundary conditions that directly determine plasma transport. The emission of charged and neutral particles affects rates of ionization and dissociation and the shapes of energy distribution functions. Boundary conductivity affects the magnitudes of electric fields that transport plasma to the surface. Surface conductivity is as important as bulk conductivity in determining the uniformity of a process both across a wafer and as a function of microstructure. Bombardment of the surface changes surface properties and thereby emission coefficients and conductivity.

While ion emission is usually unimportant, electron emission can be stimulated by electron, ion, photon, and energetic neutral bombardment. Thermal and field emission can also be significant. The relative importance of these processes is difficult to assess because surface properties—such as work function, vapor pressure, electrical conductivity, thermal conductivity, and atom mobility—are poorly known and highly variable under processing conditions. Sheath fields and current density, particularly in high-current plasmas, may also alter emission coefficients.

The description of the thermionic electron emission process from refractory cathodes based on the Richardson-Dushman-Schottky formulation is still generally accepted for arc cathodes even though evidence exists that it may not be valid for these conditions. Electron emission from cold cathodes is described by numerous authors, with the models in general describing some combination of field emission and an additional mechanism leading to microscopic evaporation sites. The models describe possible microscopic mechanisms for macroscopic observations, such as the formation of a microscopic high-pressure region in the cathode sheath emitting both electrons and ions. There have been few quantitative descriptions of arc electrode interactions at high currents (*e.g.*, 2,000 A and above), although it is known that some physical mechanisms change because of the noncontinuous change in cathode erosion rates in this current range. These high-current arcs are needed in metallurgical processing applications such as metal remelting or refining. Formulation of more appropriate cathode electron emission models is needed for thermionic as well as cold surface emission. The conditions in front of the cathode such as charged-particle density and current density, and the properties of the cathode material such as crystal structure, grain size, density, and electronic properties in addition to the work function, should be analyzed. This requires, obviously, inclusion of the solid state in the model.

A large data set exists for cold cathode spots in a low-pressure ambient and various cathode materials. Fewer data exist for cathode spots at higher pressures. Comparison with theory is hampered by the fact that direct measurements of plasmas in the micron-sized, short-lived cathode spot where pressures may briefly exceed 100 atmospheres are extremely difficult. Short-time microscopic spectrally resolved measurements of cathode spot characteristics may provide estimates of the pressure, temperature, and degree of ionization in the vapor cloud above the molten surface. The pressure dependence of the cathode spot characteristics should provide insight into the emission mechanism because of the change in current density in front of the cathode. At high current densities all cathodes become quasi-cold cathodes, and the investigation of the transition to such a state from a thermionically emitting state should provide interesting input.

Detailed descriptions exist for interaction between an arc and the anode but generally only over a limited range of parameters. The influence of fluid dynamic effects has been shown to be substantial because the boundary layer thickness determines the density gradients in front of the anode. Models exist for the onset of anode spots and for the gross evaporation of anode material, but the validity of these models for higher current arcs is unclear. The conditions for the occurrence of instabilities before the formation of anode spots need to be identified as well as the principal effects causing this mode change. The description of the anode sheath and anode boundary layer nonequilibrium region needs to be expanded to include higher current and current density conditions, which are expected to change the relative importance of the various energy exchange mechanisms. It will be important to treat these effects in two dimensions because the effect of radial energy loss, even if its magnitude is only a fraction of the axial energy flow, can be profound.

The capability of choosing the most appropriate material and thermal design for an arc electrode will have a strong impact on any application of thermal plasmas. Reduced electrode erosion translates into longer electrode life and reduced maintenance and contamination with the products of electrode erosion. The strongest impact will be in the metallurgical industry, where the size and efficiency of plasma melting installations are currently limited by the inadequate durability of electrodes.

Passive Surfaces

The influence of passive, *i.e.*, not biased or powered, surfaces on processing in both low- and high-pressure discharges is widely recognized. But our current level of understanding is severely limited because these are inherently multidimensional effects and because the surfaces are poorly characterized. For low-pressure discharges, such surfaces are usually constructed of glass, quartz, alumina, stainless steel, or aluminum. Their behavior is often determined by exposure to energetic electrons, ions, and photons and is reasonably well characterized for clean surfaces. However, when these surfaces are coated with plasma process products, their behavior is difficult or impossible to predict with our present knowledge and diagnostic capabilities.

Passive surfaces associated with high-pressure discharges, such as substrates and constrictors, are subject to large heat loads and to bombardment by particulates. Energy transfer models for cooled surfaces exist only for a limited parameter range and are insufficiently verified by experiment. Better descriptions are needed for heat transfer coefficients, chemical composition of the nonequilibrium boundary layer, homogeneous nucleation in the boundary layer, and heterogeneous nucleation on the surface.

Particulates

Discharge walls are not the only solid surfaces in contact with the plasma. Particulates formed by gas phase chemistry or sputtered from the walls typically acquire negative charges and become trapped within the discharge. In this way, they can dramatically influence plasma transport as well as affect material properties. Particulates are an undesirable side effect in etching but are the desired product in ceramic precursor synthesis. Modeling and simulation studies of particulate growth, trapping, and loss within discharges could have immediate consequences in improving manufacturing yields.

The interaction of thermal plasmas with particulates is important in several applications: (1) in plasma spraying, it is the momentum and energy exchange between the plasma and the spray powder that largely determines the quality of the coating, and considerable effort has gone into describing this interaction; (2) in plasma synthesis, *i.e.*, the plasma generation of particles from a vapor-phase chemical reaction, nucleation and particle growth processes are still poorly understood, and few diagnostic data are available; (3) in TPCVD, the avoidance of nucleation in the boundary layer in front of the substrate is usually desirable for good film quality.

Microstructure Evolution

For ion-induced etching (*i.e.*, no neutral component), profiles have been simulated from first principles by considering ion-neutral scattering in the sheath and assuming that the etching rate is proportional only to the energy flux at the surface. Remarkably good agreement with results of experiments has been obtained for the etching of photoresist in an oxygen plasma despite simplifying assumptions about the ion transport and etching mechanism. For more complicated systems, semiempirical methods have been used successfully to model profile evolution during low-pressure plasma etching and deposition. Most etching reactions are not so simple, however, and profile evolution is usually modeled by specifying vertical and horizontal etch rates for each of the films on the wafer exposed to the plasma: for example, photoresist, silicon dioxide, and doped silicon. These rates are assumed to be uniform across the wafer and independent of time and topography. They are also determined from a set of expensive calibration measurements. A new set of calibration measurements must be performed whenever process variables—such as discharge power, pressure, gas mix, film doping, and photoresist composition—are changed. Reliable models for plasma generation and transport could have a dramatic impact on profile simulation, providing that adequate models and data for etching and deposition surface chemistry also exist.

In Situ Analysis

Without proper specification of reactor operating conditions, it has been difficult at best to compare diagnostic data obtained in different laboratories or to compare laboratory results with those given by models. Such specification, of course, would also help in transferring industrial processes from one reactor to another. Currently, processes are retuned even when transferred between nominally identical reactors because there are real differences in, for example, reactor wall conditions that are not diagnosed. Real-time, in situ measurement of surface properties could revolutionize our understanding of plasma-surface interactions.

Experiments that provide measurements of surface properties during plasma operation are desperately needed. Changes in plasma emission and absorption spectra have been used to sense changes in surface conditions and implement process control, but to date this has required empirical calibration for each set of processing conditions. Despite the criticality of surface temperature in controlling plasma-surface interactions, only recently have techniques been developed for real-time, nonintrusive temperature measurement.

Other *in situ* surface analytical techniques that have been employed are deficient in providing detailed surface concentrations and charge densities. For example, ellipsometry is perhaps the most widely used real-time, *in situ* analytical technique, but it provides only a measurement of the dielectric properties of the thin film at a single wavelength. Even employing the much more powerful spectroscopic ellipsometry, one still obtains only the dielectric properties as a function of wavelength or energy. While this is valuable information and could be useful in process control schemes, a model is always needed to convert the dielectric constants to other parameters such as thin-film composition or morphology.

Light scattering has recently been applied to monitoring surface morphology during plasma processing, and photoluminescence has been used to monitor damage during etching of compound semiconductors such as GaAs and AlGaAs. But both these techniques require advances in theoretical simulation to unambiguously relate the measured quantities to surface properties.

In situ compositional information might be obtained by using techniques such as Rutherford backscattering and x-ray fluorescence. Such experiments would require an accelerator and a synchrotron, respectively, and would best be carried out as a collaborative effort between industry, academia, and a national laboratory.

FUNDING FOR PLASMA PROCESSING RESEARCH

A rigorous assessment of the funding situation for plasma processing research has been difficult to perform for basically two reasons: (1) there is no central agency that monitors federal funding of plasma processing research; and (2) most industrial concerns are unwilling to disclose the money invested in a particular research effort. Nonetheless, the panel conducted an informal survey of government funding agencies to estimate the level of federal funding for plasma processing science and technology. Results indicated that at least 14 divisions or offices within government agencies such as the National Science Foundation, the Defense Advanced Research Projects Agency, the Department of Energy, the Air Force Office of Scientific Research, and the Office of Naval Research invest a total of approximately $17 million in plasma process science and technology through a variety of programs. Of this total, approximately 25 percent goes toward programs focused on thermal plasma applications.

In addition to federal funding, industry contributes approximately $3 million per year through the Semiconductor Research Corporation (SRC) and SEMATECH. Most of these programs are focused on short-term development projects. Thus the estimated total, excluding proprietary research by chip manufacturers and plasma processing equipment vendors, is approximately $20 million per year. This sum includes funds for salaries, overhead, and operating expenses.

Most of the money from SEMATECH is invested in SEMATECH Centers of Excellence (SCOEs). Each center is focused on a particular aspect of semiconductor manufacturing technology, and Princeton University, with a strong pedigree in fusion research, is the plasma processing SCOE. Other SCOEs and universities supported by SRC that have programs in plasma processing research include the Massachusetts Institute of Technology, the University of Michigan, Rensselear Polytechnic Institute, the University of California at Berkeley, North Carolina State University, the University of New Mexico, and Arizona State University. In addition, the National Science Foundation created an engineering research center for plasma-aided manufacturing at the Universities of Wisconsin and Minnesota in 1989. Wisconsin again has a strong background in fusion research, and Minnesota has a long history of *thermal* plasma processing research.

By and large, current funding has been inadequate and insufficiently coordinated to support the generation of plasma diagnostic data, surface interaction studies, development of new *in situ* surface diagnostic techniques, simulation of plasma generation and transport, simulation of surface processes, and compilation of a minimal basic data set. Atomic and molecular physics programs are not coupled to plasma process research programs, and so what little experimental and theoretical work is being performed to generate needed cross sections and rate constants is not focused on the needs of plasma processing. This situation in the United States should be contrasted with the situation in Japan and in France.

Japanese Research

A striking difference between Japanese universities and those in the United States is the degree of cooperative research being conducted between industrial, national, and university laboratories. In almost every case, those from Japanese universities who responded to the panel's informal survey (see Chapter 5) stated that at least one or, in many cases, more researchers from industry were working as visiting scientists in their laboratories. Frequent meetings are held for presenting results, participating in problem solving, and preparing proposals. Since graduate education and research in plasma engineering are often carried out by master's candidates who have concurrent jobs in industry, industrial support and the connection to industrial needs are natural and prevalent.

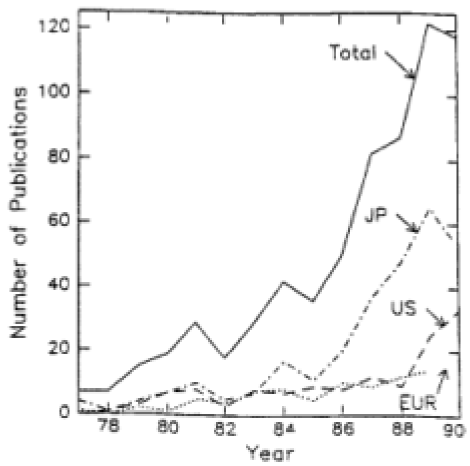

Figure 4.10
Number of publications on electron cyclotron resonance plasmas as a function of the year published. Japan has dearly been leading the research effort. (Compiled by R. Matula, AT&T Bell Laboratories.)

These cooperative research efforts are, in part, orchestrated by a national program administrated by Japan's Ministry of Education, Science, and Culture (MESC). This program, called "Grant-in-Aid for Scientific Research on Control of Reactive Plasmas," was developed in response to the MESC's designating plasma processing as a national scientific "priority" area. As a result of this designation, joint funding for universities and industry is provided. As of 1990, more than 58 universities and industrial organizations and 157 senior scientists were participating in the program.

This form of cooperative funding and research is beneficial to the field, enabling a critical number of researchers to focus their attention on a single area and providing a forum for information and technology exchange. Much of the Japanese progress in plasma processing, in universities in particular, can be traced to this program. This program is at least one reason that the Japanese have established a clear lead in electron cyclotron resonance research (Figure 4.10) and application (see Figure 3.7).

The MESC program is, in principle, similar to SRC- and SEMATECH-sponsored university research in the United States. There are, however, significant differences. The Japanese program targets a broader range of fundamental science topics (*e.g.*, measurements of electron-impact cross sections and excited-state excitation transfer coefficients). This ability to fund basic science in concert with applied science in a cohesive program is, of course, driven by the availability of funding and the willingness of universities and industry to work together. The SRC has neither the funding nor a mandate to address many basic science issues.

Another important difference between university research in the United States and Japan is the method of funding. The MESC program titled "Control of Reactive Plasmas" is currently funded at approximately $5 million for 3 years. That funding, though, represents the incremental research dollar that can be spent primarily on equipment and discretionary purchases: the salaries of permanent scientific staff, professors, and students are paid by the MESC exclusive of research grants. Senior researchers also routinely receive in excess of $40,000 per year for supporting costs and expendable supplies, and they can apply for an additional $40,000 to $200,000 per year. Considering that overhead expenses are not paid out of these funds and that salaries need not be paid out of research funds, the $5 million funding from the MESC for research in reactive plasmas is equivalent to perhaps $25 million to $30 million in the United States.

In addition to the support provided through the project on control of reactive plasmas, direct support is given to various laboratories by the MESC for plasma processing activities. For example, Kyushu University recently received $15 million for 3 years to create a plasma engineering laboratory, with about 30 percent of the effort related to plasma processing. Again, salaries for professors, students, and support staff are already paid by the ME$C.

French Research

The degree to which research is centrally coordinated on the federal level is much higher in France than in the United States. This is largely a consequence of the efforts of the Centre National de la Recherche Scientifique (CNRS). The CNRS serves as a funding agency, organizes joint research programs between CNRS facilities, universities, and industry, and coordinates summer schools and continuing education programs. Many university research groups are fully funded by the CNRS.

An example of CNRS-coordinated collaborations between universities, CNRS research facilities, and industry is the Groupe de Recherche Coordonne (GRECO) 57 program "Interactions Plasmas Froids/Surfaces (Interactions Between Cold Plasmas and Surfaces)." The objectives of this program are to coordinate research in various aspects of plasma processing, including modeling, *in situ* plasma and surface diagnostics, and materials characterization. As of late 1990, GRECO 57 focused on reactive plasmas. The applications that it targeted are deposition of amorphous and microcrystalline silicon, deposition of amorphous carbon, diamond-like and diamond films, and treatment of polymers and etching.

FINDINGS AND CONCLUSIONS

Fabrication of future microelectronic devices will demand a departure from the traditional, empirical approach to plasma process and reactor development. Reactors and processes best able to meet future device specifications will be *designed*, not empirically developed. In the case of process design, what is foreseen in the nearer term is an expert-systems approach in which basic science provides needed scaling relationships and guidance in limiting the process variable parameter space. Because of the complexity of plasma chemistry and plasma-surface interactions, first-principles models will take longer to develop, and experimentation and statistical optimization will continue to be necessary for process development. For reactor design, on the other hand, first-principles-based computer-aided design (CAD) tools can be more readily developed and will enable rapid comparison of alternative design concepts without time-consuming and costly construction of numerous prototypes.

Although basic studies have had significant impacts on previous plasma process and reactor development, the basic science needed to build design tools and expert systems is much more extensive. Three areas are recognized as needing concerted, coordinated experimental and theoretical research: surface processes, plasma generation and transport, and plasma-surface interactions. In each of these areas, there are dire needs for basic data such as cross-section and rate constant sets.

Most of our understanding of surface processes in plasma reactors has come from carefully controlled beam-surface studies, in which reactants impinging on the surface have well-controlled energy and purity and the surface is well characterized before and after reaction. Technically, U.S. laboratories have excelled in this kind of research, but poor coordination has inhibited its use in new reactor design and plasma process simulation. Sophisticated surface process simulations are being developed rapidly, and the advent of enhanced supercomputer capabilities will enhance this progress further. But little effort is currently focused on applying these methods toward trying to understand the effects of energetic bombardment and the chemical reactions that are prevalent in processing plasmas.

Models and diagnostic techniques for plasma generation and plasma transport are rapidly growing in sophistication. These are needed to simulate, understand, and control energetic bombardment of device wafers in plasmas. Because plasma generation and transport are the primary focus of new reactor design, the simulation tools already developed could be developed further and directly implemented in CAD tools. The advent of new computer technology will enable plasma simulators to meet the challenges of calculating particle energy distribution functions for multidimensional, magnetized systems. Numerical simulation will be invaluable in developing an understanding of the instabilities and turbulence in plasma reactors that currently inhibit reproducibility and control in processing. However, progress is currently impeded by lack of a reference model with which algorithms can be tested and evaluated; a lack of basic data on cross sections and rate constants that are required for making quantitative comparisons with the results of laboratory experiments; and a lack of reliable quantitative diagnostic data.

Diagnostic technology is sophisticated, but experiments are loosely focused and performed on a large variety of different reactors under widely varying conditions. A coordinated effort to diagnose a simple, reference reactor has begun to generate the necessary data base for evaluation of simulation results and to test new and old experimental methodology.

The dearth of basic data needed for simulation of plasma generation and transport results directly from insufficient funding. Data that exist are difficult both to find and to disseminate. The methods—both experimental and theoretical—exist for generation of most of the needed data. Lack of coordination between researchers generating basic data and those simulating and diagnosing plasmas also contributes to the problem. The critical basic data needed for simulations and experiments have not been prioritized.

To control plasma processes and make full use of basic surface and plasma science studies, the problems of plasma-surface interactions must be considered. Foremost among these interactions is how plasmas modify surface properties that affect emission of particles and surface conductivity. There is an urgent need for *in situ* analytical tools that provide information on surface composition, electronic properties, and material properties that relate directly to device yield. Another challenge is to couple plasma generation and transport simulation to surface processes in order to predict surface profile evolution during plasma etching and deposition.

Although the United States is making strong efforts in each of the three critical research areas, and in many cases the best efforts, these efforts are largely uncoordinated with respect to one another and are disconnected from the plasma equipment vendors who develop new reactors and processes. Funding comes from at least 14 different federal agencies as well as from separate industrial sources. Connections between surface processes, plasma generation and transport, basic data, and plasma-surface interaction research are nonexistent. This situation differs markedly from the situation in Japan and France, where research in these areas is closely coordinated between industrial, national, and university laboratories.

5

Educational Issues

Many of the challenges discussed in previous sections are rooted in the interdisciplinary nature of plasma processing, and the difficulty that any individual, or group of individuals, has in acquiring the tools necessary to carry plasma process and reactor design from inception to fruition. It is clear that the educational background of professionals in plasma processing must be simultaneously narrow, to enable them to address challenges in their individual specialties, and broad, to enable them to address the interactions between processes.

As in other high-technology undertakings, the skills required for a healthy plasma processing industry encompass virtually the entire range of technical, managerial, and support roles. One can loosely group these skills in the plasma processing industry as:

- Process science and engineering;
- Equipment design and product engineering;
- Test engineering, circuit design, system integration, and packaging;
- Equipment maintenance;
- Quality control;
- Management; and
- Sales

It is clear that professionals in each of these categories require individual specialized skills. However, it is also clear that individuals in each category require some exposure, through formal education, to the science and technology that forms the basis of their industry.

Because plasma processing is an interdisciplinary science, there are no readily available compendia that categorize scientists and engineers working in plasma processing. It was not possible for the panel to determine what company needs are for plasma processing personnel, as this is generally considered proprietary information. However, in informal polls and in discussions at the workshop, there was a clear consensus that few people working in the field have actually been trained in low-energy plasma science. Most professionals in the field have been trained as chemists, chemical engineers, physicists, plasma physicists, or electrical engineers. This situation is characteristic of the field of materials science in general (see *Materials Science and Engineering for the 1990s*, National Academy Press, Washington, D.C., 1989). There was a similar consensus that the number of high-quality students graduating with training in low-energy plasma science or plasma processing research is insufficient.

The panel has estimated the numbers of professionals required to maintain a healthy U.S. plasma processing industry, considering both the market value of products directly produced by the industry and the observed trends in high-technology companies such as computer manufacturers, which have revenues of approximately $100,000 to $300,000 per worker. The current worldwide market directly in plasma processing is $1 billion (plus $800 million in plasma spraying) and will grow to $2 billion ($3.5 billion including spraying) by 1995 (see Figure 3.1), of which approximately half is in the United States. This suggests a need for 2,500 to 5,000 U.S. professionals with expertise in plasma processing. Assuming that at least 10 percent of these people are replaced annually by either normal attrition or additions for growth, the U.S. plasma processing industry needs at least 250 to 500 new professionals annually.

The skills and educational level required by these people will be varied, but the majority of these needs can be satisfied by training on the B.S. and M.S. levels. However, faculty must be educated first before they can prepare undergraduates for careers in plasma processing. Maintaining world leadership in plasma processing requires a healthy educational infrastructure that produces both B.S./M.S. and Ph.D. graduates with the skills required to quickly contribute to the industry.

If we do not prepare our faculty and students to meet the plasma processing needs of industry, the cost will be high. On-the-job training in high-technology industries requires an estimated 3 years before a new hire can be assigned full project responsibility. This time should be compared to the 6 to 9 months required for a well-trained, well-educated professional to master the same job. The cost to the national economy of on-the-job training in the plasma processing industry will be approximately $125 million to $250 million annually. Considering that this cost leverages a $1 billion to $2 billion plasma equipment industry, which in turn leverages a $17 billion to $38 billion microelectronics industry, the importance of adequately trained professionals cannot be overestimated.

These costs to the national economy should be compared to the costs of improving the educational infrastructure to provide proper education and training. Five hundred new professionals per year means that 10 universities must each produce 50 graduates per year to work in the plasma processing industry. Providing annual university grants of $500,000 each to 10 universities for sustaining and promoting research and education in plasma processing seems a small price to pay when compared to savings from on-the-job training and the ripple effect that a strengthened electronics industry will have on the economy at large.

The discussion in the remainder of this chapter focuses on educational needs for proper training of plasma processing professionals: the preparation researchers need to be able to contribute to the field; educational offerings for undergraduates, graduates, and professionals; and how the United States rates in the preparation of workers compared to Japan and the European Community.

EDUCATIONAL REQUIREMENTS FOR UNDERGRADUATES

In this discussion of key components of the curriculum for undergraduate scientists and engineers preparing to work in plasma processing, two major themes are emphasized. First, plasma processing is highly interdisciplinary. Undergraduate students must be encouraged to take courses from a variety of academic departments. Second, plasma processing is now a largely empirical science. To be successful in this field an undergraduate must obtain a working knowledge of the scientific method and proper laboratory training.

To obtain the broad background needed to contribute in a technical role in the plasma processing industry, courses in the following areas are essential:

- Atomic and molecular physics,
- Chemistry and chemical kinetics,
- Computer science,
- Electromagnetic theory,
- Plasma and glow discharge physics,
- Condensed matter and materials science, and
- Processing and manufacturing technology.

Laboratory Courses and the Scientific Method

Students intending to specialize in plasma processing, as well as the general technical student, would benefit greatly if experiments in discharge plasmas were incorporated into existing intermediate and advanced undergraduate laboratory courses. For example, measuring electron densities using a Langmuir probe in a sealed mercury-vapor glow discharge tube is a straightforward and inexpensive experiment.

The need for obtaining adequate laboratory experience on the undergraduate level affects most high-technology industries, and plasma processing in particular. Although great efforts have been made to provide this instructional infrastructure, the current situation with respect to laboratory courses is, in many cases, not satisfactory, and undergraduate laboratory experiences are inadequate. As a result, all technical undergraduate students suffer, particularly those who intend to specialize in plasma processing. Modern instructional laboratory courses are expensive to establish and maintain. In times of inadequate funding, discretionary resources are often allocated instead to other activities.

As a result of plasma processing now being an empirical science, the undergraduate must obtain a working knowledge of the scientific method. Research in plasma processing is "small" science, and the scientific method is practiced in a very traditional fashion. A working knowledge of the traditional scientific method is not taught in formal courses; its practice can only be taught in well-conceived laboratory courses (either experimental or computational) or through research projects.

The National Science Foundation (NSF) has recognized the importance of maintaining undergraduate laboratories and has started the Instrumentation and Laboratory Improvement Program to address the problem. This program could be strengthened by targeting specific high-priority areas of national importance, such as plasma processing. Additional programs funded by other agencies and foundations are also required to augment the efforts of the NSF, since its resources are limited and the need for improving the undergraduate infrastructure is great.

Research Experiences and Cooperative Programs

Research experiences for undergraduates help develop laboratory and computer skills and teach the scientific method. The NSF sponsors the Research Experience for Undergraduates Program, which provides funding for this purpose. The national laboratories and many corporate laboratories offer summer internship programs and cooperative programs. The Cooperative Education Association Inc. is doing an excellent job of developing, promoting, and implementing the concept of cooperative education. These programs are all valuable, but they should be strengthened to address high-priority areas such as plasma processing. This could be accomplished by cooperative funding of student internships between federal agencies and industry, which could also enable the smaller yet important equipment vendors to take part in these valuable programs.

Cooperative programs during the summer for high school science teachers provide an important opportunity for introducing plasma technology into public school courses. Industries and universities could provide research opportunities for public school teachers in the same manner that these opportunities are made available for undergraduate students.

U.S. GRADUATE EDUCATION

To survey current curricula for graduate students preparing to work in the field of plasma processing, the panel examined course catalogues to determine how graduate programs are tailored to meet the needs of industry. Fourteen major universities and 76 departments where faculty are involved in plasma research were surveyed.

In the panel's informal survey, 160 courses were identified as primarily plasma science courses. The panel's general conclusions from the survey were that (1) these institutions adequately cover subjects related to highly ionized, weakly collisional plasmas as found in fusion research; and (2) these institutions, with few exceptions, are not adequately covering concepts related to weakly ionized, highly collisional plasmas as found in plasma processing research. Most of the courses do cover important topics such as Debye screening, plasma frequency, single-particle motions in electric and magnetic fields, fluid models of plasmas, and kinetic theory. But, for the most part, graduate-level plasma science courses are not preparing students in the physical sciences and engineering to work in the field of plasma processing. Graduate-level courses are controlled by faculty interests, and deficiencies in plasma science curricula directly reflect the small number of academic research programs in plasma processing.

Areas that are vital to a healthy education in plasma processing but that have received inadequate attention in most graduate curricula include the following:

- *Fundamentals of electron collisions*. Less than 10 percent of the courses surveyed cover fundamentals of electron-atom/molecule and ion-atom/molecule collisions. These types of collisions are dominant in weakly ionized plasmas. The fundamentals of Coulomb collisions, dominant in fusion plasmas, are discussed in a majority of the courses. Only one plasma course in the survey includes multistep ionization in its formal syllabus, although the topic is known to be more widely addressed. Electron impact processes involving excited states of atoms and molecules can dominate the ionization balance of both dc and rf discharges over a wide variety conditions, and exposure to these concepts is important to engineers and scientists working with low-temperature plasmas.
- *Hydrodynamic approximation*. Less than 5 percent of the courses surveyed cover the local field or hydrodynamic equilibrium approximation as a formal syllabus item, although the topic is known to be more widely taught. This is a fluid approximation in which electron and ion transport coefficients are parameterized in terms of the ratio of the electric field to gas density. This approximation is important because it is the starting point in modeling most plasma reactors, and most experimental data on electron transport coefficients are obtained using the local field approximation.
- *Plasma reactor technology*. Less than 10 percent of the courses surveyed cover fundamentals of direct-current, radio-frequency, and microwave plasma reactors. This is a serious deficiency since plasma reactor geometry and power coupling schemes are important factors in process design. Any professional working in plasma processing requires exposure to these concepts.
- *Radiation transport*. Less than 5 percent of the plasma courses surveyed cover radiation trapping and radiation transport. Optical transitions from excited levels to the ground level of atoms and molecules in discharges are often optically thick. Diagnosing low-pressure plasmas must take these effects into consideration. Power that is optically emitted and absorbed in high-pressure plasmas can sometimes play a dominant role in the power balance.
- *Plasma chemistry and plasma technology*. Less than 5 percent of the courses surveyed cover fundamentals of plasma chemistry or the collisional/radiative rate equation models that are used to describe plasma chemistry. There are, no doubt, other courses that offer this educational background. The fact that they are "hidden" from courses associated with plasmas is a weakness. Finally, only 5 to 10 percent of the courses surveyed cover fundamentals of etching and deposition.

TEXTS AND COMPUTER-AIDED INSTRUCTION

The content of graduate-level courses is at least partially influenced by the content of textbooks. Most introductory graduate-level courses in plasma science are taught from the texts that were written primarily for students intending to work in fusion research. In these texts there is rarely any mention of charged particle-neutral particle collisions, important concepts such as the local field approximation, or technologies such as etching or deposition. Many courses emphasizing collisional plasmas rely on material from classic older textbooks such as *Basic Data of Plasma Physics* (MIT Press, Cambridge, Mass., 1967) by S.C. Brown and *Ionized Gases* (Clarendon Press, Oxford, 1965) by A. von Engel. Unfortunately these texts are out of date and out of print. There are a number of Russian translation texts (*e.g*., Smirnov's *Physics of Weakly Ionized Gases*, B. M. Smirnov, translated by Oleg Glebov, MIR Press, Moscow, 1981, and Biberman's *Kinetics of Nonequilibrium Low-Temperature Plasmas*, L. M. Biberman, V. S. Vorobev, I. T. Iakubov, Consultants Bureau, New York, 1987, translation of the Russian *Kinetica Neravnovesnofi Nizko-Temperaturnofi Plazmy*) that serve well as supplementary texts, but not as primary teaching tools.

The lack of textbooks in collisional plasma science extends to plasma technology. The few existing graduate-level courses on plasma processing are taught primarily from notes. Although there is an excellent series of monographs on plasma processing currently being published (*Plasma-Materials Interactions*, edited by O. Auciello and D. L. Flamm, *Plasma-Surface Interactions and Processing of Materials: Proceedings of the NATO Advanced Study Institute on Plasma-Surface Interactions and Processing of Materials*, Alicante, Spain, Kluwer Academic Publishers, Dordrecht, Boston, 1990), these books were not intended to be used as texts. The lack of textbooks in the field is highlighted by the continued use of older monographs for instructional purposes. *Glow Discharge Processes* (Wiley, New York, 1980) by Brian Chapman first appeared in 1980 and is commonly used for undergraduate and graduate courses. Although it is an excellent introduction to the field, more current offerings are needed.

Computer-aided instruction, now often used in first-year physics and chemistry courses, is not commonly associated with upper-level undergraduate and graduate courses. The Plasma Simulation Group at the University of California at Berkeley has developed user-friendly, portable programs, capable of being run on personal computers for use in computer-aided instruction. More programs of this type could be offered in teaching plasma-surface interactions such as profile evolution during etching and deposition.

FACULTY DEVELOPMENT

The lack of graduate courses and programs in plasma processing is directly attributable to a lack of trained faculty, which in turn relates to the inadequacy of research funding. This need can be partly satisfied by improving ties between universities, national laboratories, and industries. "Co-ops" for faculty in industry and national laboratories, and visiting academic appointments for industrial researchers, would greatly aid in cross-training of these individuals. These programs should be directly supported by both industry and government.

CONTINUING EDUCATION

Because plasma processing is interdisciplinary and is rapidly expanding in the industrial sector, scientists and engineers trained in other disciplines are continually entering the field. It is also the norm for new hires to have no formal training in plasma processing. Given these conditions, continuing education is vitally important.

Most large industrial research laboratories active in plasma processing have established in-house continuing education courses for their employees. The majority of continuing education opportunities, though, are offered by third parties: consultants and professional societies. The Materials Research Society (MRS) and the American Vacuum Society (AVS) are the primary coordinators of postgraduate short courses in plasma processing. These organizations offer at least seven courses directly related to plasma processing, and at least an additional eight with a portion of their content addressing plasma processing. Courses are also offered by the Society of Photo-Optical Instrumentation Engineers (SPIE) and the Electrochemical Society (ECS).

Students from more than 280 companies have taken the MRS and AVS short courses directly addressing plasma processing during the past 6 years. This list encompasses virtually all major companies active in plasma processing. A surprising number of university employees or students have also attended these courses, attesting to the lack of those courses on their home campuses.

FOREIGN EDUCATIONAL OFFERINGS

To objectively assess the status of U.S. educational offerings in plasma processing, it is important to make comparisons with those in foreign countries. One indication of the importance that foreign competitors place on plasma processing is their commitment to relevant educational programs.

A comprehensive study of the education in plasma processing offered by foreign universities is beyond the scope of this report. However, the panel informally surveyed foreign researchers active in plasma processing, soliciting information on degree programs, course offerings, cooperative programs, and postgraduate education. More than 60 researchers in 12 countries were queried, and more than 50 percent responded. Additional input was obtained from panel members touring foreign laboratories (principally in Japan) and from published descriptions of national programs (again, principally in Japan).

The responses varied in detail, but some provided extensive summaries of educational offerings in plasma processing in their countries. Universities in Eastern Europe with a long, rich history of research in collisional plasmas are now focusing on plasma processing. Although cooperation between universities and government laboratories is greater in Eastern Europe than in the United States, coordination of that research is no better.

Below, the panel highlights educational programs in Japan and France, on which the most information was obtained.

Japan

According to the panel's informal survey, course offerings in plasma processing and collisional plasmas at universities in Japan are generally comparable with those in the United States. They vary widely from campus to campus, primarily relying on the interest of individual faculty to sponsor courses. There are, however, notable exceptions. Keio University has three undergraduate and two graduate courses, with a combined enrollment of more than 120, directly related to collisional, low-energy plasmas. Tokyo Institute of Technology has an annual enrollment of 40 to 70 students in courses directly related to plasma processing, while the University of Tokyo has undergraduate and graduate courses in plasma processing. Similarly, Hokkaido University has three undergraduate courses and two graduate courses in topics related to low-energy, collisional plasmas. Kyushu University has a required course in gaseous electronics for electrical engineering undergraduates and an optional plasma engineering course, in addition to a graduate course that is oriented more toward fusion. By contrast, this panel is aware of no required courses in plasma technology at undergraduate institutions in the United States.

It is interesting to note that many courses relating to collisional plasmas in Japan trace their origins to gas laser technology. In a national program sponsored by the Ministry of Education, Science, and Culture (MESC), a commitment was made to develop gas laser technologies for materials processing. This commitment spawned courses in high-voltage engineering, plasma engineering of lasers, and applied electron physics. The plasma processing community has benefited from all of them.

Like universities in the United States, Japanese universities do not have formal degree programs in plasma processing, but rather fold plasma processing into existing degree programs. Opinions expressed on the availability and suitability of texts on plasma processing were quite varied, leading the panel to conclude that there are no universally accepted texts for use in these courses.

France

The results of the panel's informal survey indicate that French graduate education in plasma processing operates much like that in the United States. In general, plasma processing researchers are scattered among many departments. There are, however, many degree programs in France, either in place or pending, that specialize in nonfusion and nonspace plasmas. The majority of them are classified as Diplome d'Etudes Approfondie (DEA). These are sometimes temporary degree programs that are approved by the Ministry of Research and Technology and associated with a particular university or CNRS facility. There are typically 20 students in each program. The degree programs, equivalent to an M.S. degree in the United States, consist of an academic year of course work. At the end of the year, students are required to complete a short research project (duration of approximately 3 months) either at the university, at a CNRS facility, or in industry (public or private). A final oral presentation is reviewed by both university and industrial representatives.

Some of the DEA programs having direct application to plasma processing are listed below.

- Université Pads VI—Génie des Procedes et Chemie Applique: This program of study deals with plasma-surface interactions and rf discharge reactors.
- Université Pads VI—Electrotechnique: Plasma engineering with emphasis on atmospheric pressure plasmas (switches, corona discharges, arcs).
- Université Pads Sud—DEA de Physique des Gas et des Plasmas: This program has fairly comprehensive course work on basic collisional plasma physics, plasma-surface interactions, plasma diagnostics, modeling, plasma chemistry, and laboratory practices. It is closely aligned with CNRS.
- Université Paul Sabatier, Toulouse—Génie des Procedes Plasmas: This program, begun in the fall of 1991, will specialize in collisional plasmas and will include basic courses in plasma physics, macroscopic properties of discharges in gases, plasma diagnostics and principles, discharge lasers, and plasma processing. An existing degree program (Diplome d'Etudes Approfondie de Physique des Plasmas) specializes in plasmas but prior to 1990 did not emphasize plasma processing applications.
- Université Nantes: There are DEA programs in both materials science and in electronics. Although not specializing in plasma processing, they have a high level of course content in the area. The pertinent topics include plasma materials interactions and plasma modeling.

There are other DEA and degree programs emphasizing materials processing at Université Pads XI at Orsay, Université de Orleans, and Université de Limoges.

A goal of the CNRS-sponsored Groupe de Recherche Coordonne (GRECO) 57 is to disseminate "fundamental knowledge" in plasma processing to researchers in other institutions or industry by organizing open meetings and summer schools. Two books (in French) have been published following such summer schools: *Reactivite dans les plasmas: Applications aux lasers et au traitement de surface* (Reactivity in Plasmas: Applications to Lasers and Surface Treatment; A.M. Pointu and A. Ricard, eds., Les Editions de Physique, 1982) and *Interactions plasmas froids materiaux* (Interactions of Cold Plasmas with Materials; GRECO 57 du CNRS, Les Editions de Physique, 1987). These texts have been very well received by students in introductory courses on plasma processing. A summer school held in parallel with the 8th Colloque International sur les Procedes Plasmas (CIP 91) will result in publication of a new text, *Depot et gravure chimique par plasma* (Plasma Chemical Deposition and Etching; GRECO 57 du CNRS and Société Francaise du Vide, 1991).

FINDINGS AND CONCLUSIONS

The United States is not adequately preparing for the rapid growth of plasma processing in materials processing applications. As a result, on-the-job training will be necessary to remain competitive. However, such training is inherently costly when compared to investment in the educational infrastructure. Worse, the time lost in on-the-job training may result in missing market windows for new products and may present economic obstacles that can be difficult or impossible to overcome.

Although undergraduate curricula at universities in the United States generally include the necessary lecture courses to prepare students to work in the field of plasma processing, survey and introductory courses in plasma science and technology are lacking. Survey courses are particularly necessary to acquaint nontechnical students with the basics of high-technology industries such as plasma processing. Progress toward these goals can be made by incorporating the physics of collisional plasmas into existing and improved laboratories, and general science courses.

Because of the interdisciplinary nature of plasma processing, the available courses are scattered throughout many departments. Although the benefits of establishing undergraduate degree programs in plasma science are not clear, it is clear that undergraduates would benefit greatly from interdepartmental non-degree programs that serve to advise and direct students toward these courses.

The most serious needs in undergraduate education are properly trained and educated teachers and professors as well as adequate, modern teaching laboratories. Internships in industry for faculty interested in learning about plasma processing do not exist. Proper training in the traditional scientific method, as provided in laboratory classes, is a necessary component of plasma processing undergraduate education but is not emphasized sufficiently. The Instrumentation and Laboratory Improvement Program sponsored by the NSF has been only partly successful in fulfilling these needs. Industrial cooperative programs, internships, and research experiences for undergraduates through industrial cooperative programs or internships are essential for high-quality technical education.

Graduate curricula are, for the most part, not offering adequate exposure to the science of weakly ionized, highly collisional plasmas. The panel's survey of current curricula shows that only a few U.S. universities have formal course work in this science. Since specialty graduate courses are taught by professors who are actively conducting research in those areas, the lack of courses is a direct result of there being little funding for graduate research in plasma processing and low-energy plasmas. The lack of good texts on collisional plasmas and plasma processing is a serious problem, although modern texts do exist in French, Japanese, and Russian. English translations are mostly unavailable.

The level of support for plasma processing at U.S. universities is not adequate to attract the quality and quantity of graduate students needed by the U.S. plasma processing community. Federal support could provide an important incentive to forge the necessary industry-university links. Education in plasma processing in the United States lags behind that of our principal competitors in the field: Japan and Western Europe. The U.S. educational infrastructure in plasma processing lacks focus, coordination, and funding when compared to the infrastructures in both Japan and France. There are no formal graduate degree programs in plasma processing in the United States. It is clear that formulating and maintaining degree programs not only motivates the development of new courses and textbooks, but is also a more visible vehicle for attracting students to the field.

Continuing education offerings and short courses play a valuable role in training newcomers to the field and supplementing the education of specialists. Since short courses and in-house offerings are very much market driven, they both respond to and reflect the needs of the community. They also represent a valuable source of educational materials, as the notes from many of these courses serve as introductory texts. The fact that university personnel are regularly attending short courses reflects a lack of and need for similar offerings in universities.

Appendix

Participants in Workshop on Plasma Processing of Materials

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