

The Engineering Research Center for Plasma-Aided Manufacturing

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Invited Paper

Plasma-aided manufacturing, the use of electrically charged particles in the manufacturing process, is used for producing new materials with unusual and superior properties, for developing new chemical compounds and processes, for machining, and for altering and refining materials and surfaces. It has direct applications to semiconductor fabrication, materials synthesis, welding, lighting, polymers, anticorrosion coatings, machine tools, metallurgy, electrical and electronics devices, hazardous-waste removal, high-performance ceramics, and many other items in both high-technology and the more "traditional" industries. This paper describes the activities of the National Science Foundation's Engineering Research Center for Plasma-Aided Manufacturing at the University of Wisconsin-Madison and at the University of Minnesota. Participation includes a consortium of more than 30 industrial corporations.

I. INTRODUCTION AND VISION OF THE CENTER

Plasma-aided manufacturing, which we define as the use of electrically charged particles in the manufacturing process, is an emerging field that will greatly enhance the international competitiveness of the American industry. Plasma-aided manufacturing is used for producing new materials with unusual and superior properties, for developing new chemical compounds and processes, for machining and for altering and refining materials and surfaces.

In order for plasma technology to be used in manufacturing, it is necessary that superior products result, the plasma technology be more economical, or the processing result be unattainable by other methods. However, plasma-aided manufacturing is now at a critical point in its development. In the past, it has been possible to produce "industrial" plasmas for use in manufacturing with limited knowledge of the plasmas, their chemistry, their specific process control, quality and productivity improvement, and sophisticated production techniques. Now our industrial colleagues tell us

that, without in-depth understanding of the variety of phenomena taking place and their application to the industrial environment, advances in this technology, and its efficient use, will occur at a diminishing rate [1]. Specifically, our industrial partners have expressed concerns about yields, end-point detection, reliability, processing rate, aging, and feasibility of various plasma processes. They believe that significant progress demands a cross-disciplinary effort beyond the capability of any single existing U.S. industrial or university research group.

An illustrative diagram of the various reactions taking place in a plasma processing reactor is shown in Fig. 1. Every plasma reactor incorporates the following processes

- electron impact ionization and dissociation,
- gas phase chemical and physical reactions,
- surface phase chemical and physical reactions.

To maintain the discharge, ionization must occur so as to sustain the plasma. Electrons are needed to dissociate the feedstock gases to produce fragmented neutrals that are chemically active (free radicals). In addition, the ions are often needed, either by themselves or in conjunction with other species in the plasma, to produce the needed chemical reactions, in the plasma itself or on the surface of the material to be processed. Often, the gas-phase chemical reactions tend to be a loss mechanism for the free radicals, similar to the recombination processes for charged particles. On the surface itself, very complex processes occur in which the free radicals, ions, and other particles impinge upon the surface causing implantation, sputtering, deposition, or etching, or a combination of a number of these processes. These processes are often difficult to quantify.

When plasmas are used in manufacturing, the application and character of the processes involved are governed by the operating pressure of the system. The thrust areas of the ERC have been chosen to cover a progressive range of operating pressures from below 10^{-4} torr to greater than atmospheric pressure. The types of processes used in manufacturing are shown in Fig. 2 as a function of

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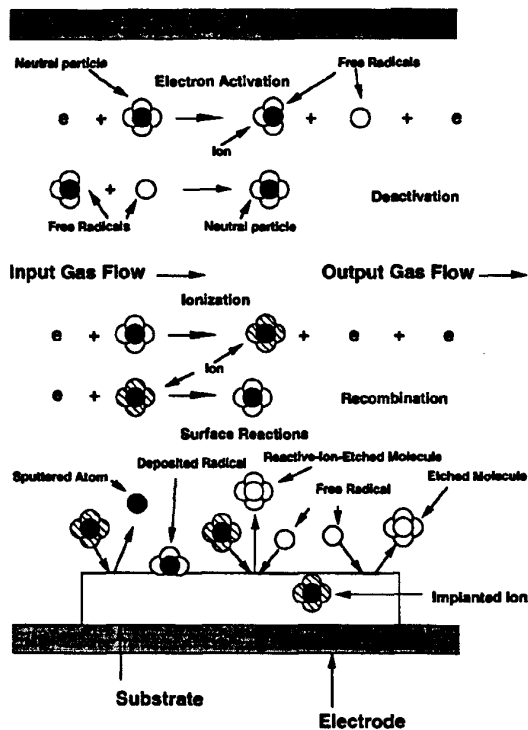


Fig. 1. Processes occurring in a plasma reactor.

operating pressure of the reactor. At low pressures, physical rather than chemical effects dominate. This is the case in thrust area 4, plasma modification of materials, for example. As the pressure increases, chemical effects begin to become significant, as in thrust area 1, plasma etching and microwave processing for microelectronics. At higher pressures, as in the case of thrust area 2, plasma deposition and polymerization, deposition effects tend to dominate, and at the highest pressures, as in thrust area 3, thermal plasma spraying, chemical vapor deposition (CVD), and sintering, the plasma tends to be used primarily as a heat (thermal) source. Viewed in this way, not only does the ERC cover the complete range of pressures used in plasma-aided manufacturing but it is clear that there are many connections that occur between the various projects and thrust areas. Each of them, for example, has surface and materials issues; needs knowledge of the gas and surface temperatures and the densities of the various species making up the plasma; and needs to develop a modeling capability that can predict the properties of the materials being processed. To ensure support to the thrust areas and to provide connections across them, the ERC has established three support groups in the areas of diagnostics, theory and modeling, and engineering statistics. We anticipate that additional support groups may be established if funds permit, especially in the area of manufacturing systems.

Accordingly, the relationship between the "external" process variables, such as RF power, gas pressure, gas

flow rate, etc., which are those variables that can be set externally to the reactor; and the "internal" process variables, such as charged particle, free radical and neutral particle concentrations and fluxes need to be determined. As an example of how a given Thrust Area is organized in the ERC to meet this requirement is shown in Fig. 3.

Finally, in order for plasma-aided manufacturing to continue to have an impact on the competitiveness of U.S. industry, it will be necessary to have future generations of engineers advance the technology of our field. Thus, our educational program is woven entirely within the fabric of our ERC. Each thrust area involves students at the undergraduate and graduate levels which exposes them to the ERC concept in the course of their activities in the research program. We also have a major effort in education involving elementary-, middle-, and high-school students, undergraduates enrolled at other colleges and universities, and adult students returning to higher education.

II. STRATEGIC GOALS

The strategic plan of the ERC is summarized in the following goals:

- Develop new processes to ensure that plasma-aided manufacturing will satisfy the present and future requirements of industry.
- Develop new diagnostics, sensors, modeling, statistical, and control strategies for plasma-aided manufacturing.
- Use and develop modern statistical techniques of experimental design and analysis to: 1) accelerate the experimental work of the Engineering Research Center; and 2) to bring new industrial processes on line with high productivity, high quality, and high reliability.
- Conduct the necessary basic science and engineering support studies needed to fulfill the mission of the ERC.
- Provide a unified cross-disciplinary experience for the large number of students interested in entering this exciting and demanding field of high technology, and expose a large segment of the graduating engineers to new concepts of design and systems integration in this area.
- Foster and maintain strong relationships between universities, industry, and government for information exchange and technology transfer.

Advances in the research base will contribute new insight for the long-term improvement of plasma-aided manufacturing. Each thrust area has varying levels of research-base advances; however, these advances are not exclusive to the thrust area in which they are investigated. Collaboration and exchange of results occurs on a continuous basis across thrust areas.

In connection with monitoring and control of the manufacturing processes, for example, three important plasma diagnostics, which we are implementing, have not routinely been used in industry for control and monitoring. They are: laser-induced fluorescence [2], infrared diode laser

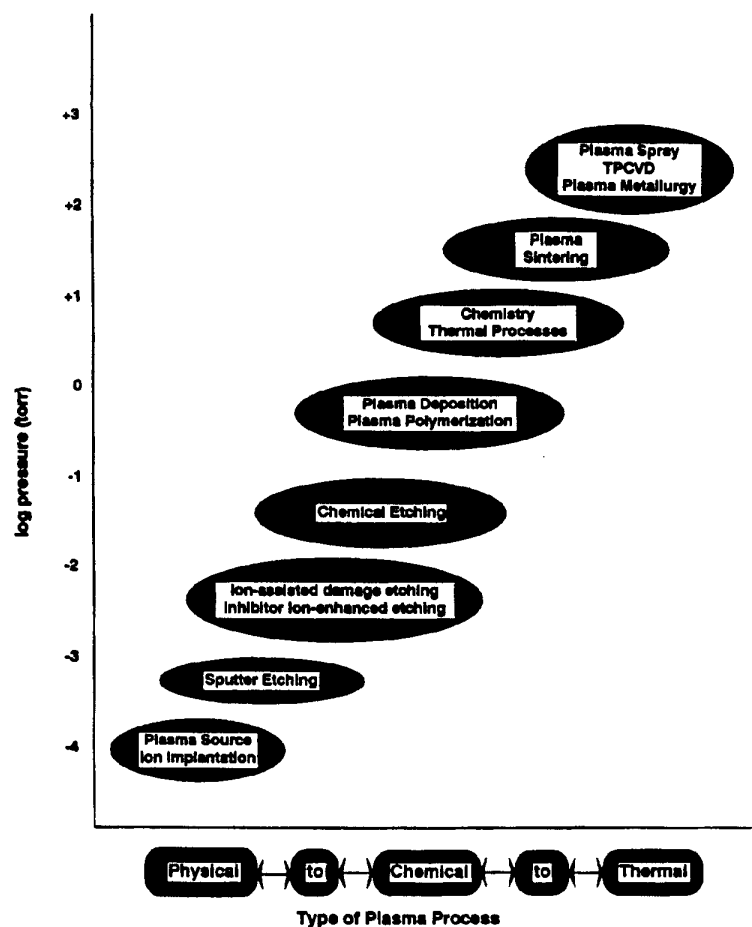


Fig. 2. Types of plasma processes. As the pressure increases, the nature of the process tends to change from physical to chemical to thermal, but in general each of them occurs in varying degree.

absorption [3], and vacuum ultraviolet (VUV) emission. We are also planning to implement Fourier-transform infrared spectroscopy in the coming year. To advance the research base in this area, we are interfacing these diagnostics with a number of reactors currently available and constructing new prototype systems that can be used to determine and control the critical process parameters for a viable system for both etching and deposition.

Advances will also be made toward a better understanding of nucleation, growth, surface diffusion, interfacial roughness, stress, and surface chemistry of plasma-deposited films. We are determining the influence of plasma processing parameters on these properties using a variety of *in situ* diagnostics. Particular attention will be directed toward understanding the plasma chemistry using our new diagnostic tools (IR absorption, laser-induced fluorescence). An important effort will be directed toward modeling of film growth in the plasma environment based on statistical design techniques. Specifically, we will explore the influence of 1) film thickness, density and stress on optical

properties; 2) plasma modification of surfaces; and 3) growth of external polymeric surfaces.

Problems in the current technology associated with plasma-aided manufacturing are: the lack of process reliability and optimization, the lack of an engineering base with which to develop process control as well as to transfer the technology to industry, and a limited knowledge to further expand the applications of the processes. In light of these problems, we have established specific technological goals for each of the thrust areas. They are as follows:

- 1) Increase process reliability for plasma etching and expand applications through increased knowledge of the potential for plasma etching using a variety of commercial and novel plasma sources.
- 2) Control the microstructure in plasma deposition processes and increase control over surface treatment processes so that desired material properties for deposited nonorganic coatings, barrier coatings, and plasma treatment of polymer materials may be

Strategic Plan

INTEGRATE THE RESOURCES OF
THE ERC TO ACCOMPLISH THE
MISSION AND GOALS OF THRUST
AREA II

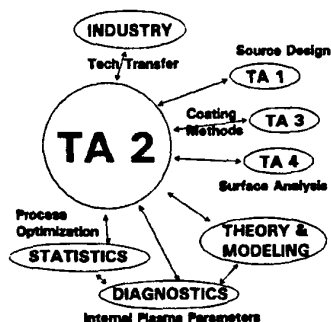


Fig. 3. Organization of a typical thrust area.

produced, optimized and scaled to a manufacturing process.

- 3) Broaden the engineering base associated with thermal plasma chemical vapor deposition necessary for developments on an industrial scale, and gain an understanding of the correlation between the plasma parameters in the plasma spray process so as to optimize the properties and quality of the coatings produced.
- 4) Determine the relationship between plasma parameters and the quality of the deposited and/or implanted material properties so as to develop processes and controls and to extend the method to the treatment of new materials.

These technological and research strategies have been further cultivated in the form of research strategies for each of the four thrust areas and support groups.

III. UNIQUE RESEARCH ISSUES

We show here a capsule summary of the current status of the activities in each thrust area being undertaken in the ERC. Upon examination of them, it is clear that although some of these could certainly be undertaken by an individual principal investigator, the combined effort is greater than the sum of the parts—in both effectiveness and coordination.

In thrust area 1, etching experiments are underway in three plasma-etching tools (a 13.56 MHz parallel plate system, a magnetically confined 13.56 MHz reactor system, and a 2.45 GHz electron cyclotron resonance (ECR) system), with wafers patterned with both X-ray lithography and conventional lithography. A variety of diagnostics have been operated in all tools. In the ECR tool, the combination of modeling and data from three diagnostic techniques laser-induced fluorescence (LIF), Langmuir probes, and a new pitch-angle diagnostic (PAD) has yielded a consistent picture of the ion distribution function at the wafer sheath-plasma boundary. The ion energy both parallel and

perpendicular to the magnetic field was found to be much less than previously suggested [4]. Modeling of the ECR plasma shows that charge exchange has three effects; the ambipolar potential is reduced lowering the maximum ion energy, ion velocity is slowed by collisions, and a cold ion species is produced by charge exchange [5],[6]. The first absolute measurements of free radical concentrations (of CF₂) in an etching plasma have been made in the ECR tool. Feedback control studies have been conducted in the RIE system using the in situ etch rate from a laser interferometer as the process monitor. First measurements with the PAD have yielded the ratio of ion perpendicular temperature to parallel ion energy on the ECR system [7]. The VUV emission diagnostic is operational.

In thrust area 2, a plasma deposition technique for polymer films for integrated optics/photonics applications has been developed. The advantages include highly conformal coatings, excellent adhesion and novel film properties that can be tailored by varying the plasma parameters. In particular, using engineering statistics, it has been shown that the refractive index of polymethyl methacrylate (PMMA) in the visible region can be varied from 1.52 to 1.62 by varying the RF power during deposition [8]. This is a remarkably large variation in index and can allow the development of graded index (GRIN) polymer channel waveguides for photonics applications. These films can also be used in optical interconnects. By using plasma/micromachining techniques, we have addressed the off-chip to on-chip interface problem inherent in optical computing. Statistical experimental design software for plasma polymerization that runs on a PC has been developed. New initiatives in ECR deposition, barrier coatings, and treatment of fibrous materials have been initiated including several novel designs for large-area variable-geometry plasma sources. *In situ* stress diagnostics for plasma-deposited polymers have been installed.

In thrust area 3, which is carried out primarily at the University of Minnesota, the technical focus has been further strengthened and there is a stronger interaction with non-ERC funded programs. Liaison representatives to the theory and modeling and diagnostics support groups have been designated. Faculty from the Minnesota Electrical Engineering and Chemistry departments have joined the thrust area. Plasma jet models have been simplified. A hot anode gas shrouded torch with a converging nozzle has been constructed which results in improved jet stability [9]. A thermal plasma CVD reactor for atmospheric deposition of diamond films is now operational with films being deposited at very high rates [10]. YSZ/High Tc superconducting films have been deposited, and new film-substrate deposition experiments with carbon and carbide films have been performed. Plasma sintering has been extended to Hafnium, which allows the operation of arc cathodes in oxidizing environments. LIF diagnostics are now operational.

Thrust area 4 shows good penetration for plasma source ion implantation (PSII)¹¹ down deep bore holes (0.5 in. diameter × 3 in. depth), which has direct relevance to

ERC ORGANIZATIONAL CHART

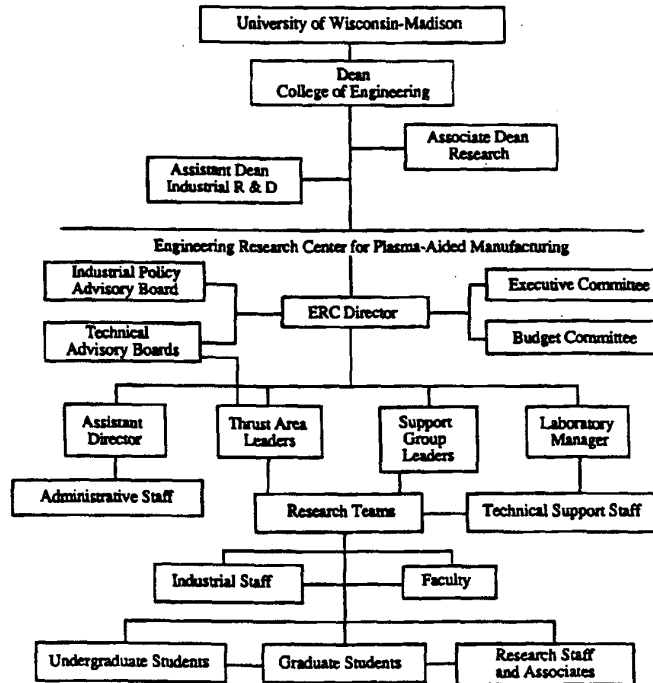


Fig. 4. ERC organization chart.

trench implantation in microelectronics. Corrosion-resistant layers of chrome-moly, 1 micron thick, have been deposited on 304 stainless steel, which reduces the corrosion rate in 0.1N sulfuric acid by a factor of 1000. This has been accomplished with independent Cr and Mo sputtering sources. Ion beam enhanced deposition (IBED) has produced a stoichiometric CrN layer on 52 100 bearing steel by alternately depositing Cr and implanting with N. Substrate temperature and PSII parameters have been varied to optimize the film growth. Oxygen PSII has been demonstrated with the implantation of MoS₂ films. Nitrogen has been implanted in Ti-6Al-4V via a two-step process: high dose, high temperature, followed by nominal dose, ambient temperature [12]. This has produced a 0.5-micron layer with tribological properties superior to the Co-Cr alloy, which Ti-6Al-V is replacing for orthopedic applications. Fundamental studies of C implantation in pure Fe are being conducted to provide insight into carbon implantation of steels. Stoichiometric TiN was produced on Inconel 718 by IBED. A corrosive wear tester has been constructed and is now operational. Ongoing field tests of PSII are under way at 12 companies.

IV. ORGANIZATION

The ERC is a cross-disciplinary organization involving faculty, staff, and students from two universities and representatives from industry, other universities, and national laboratories in research, educational, and technology trans-

fer activities. The director takes an active role in managing, organizing, participating in, and leading all the activities of the ERC. The assistant director manages the activities of the ERC and takes an active role in policy development. There are four thrust-area leaders and three support-group leaders who supervise the day-to-day activities of the thrust areas and support groups and participate in setting policy through an executive committee.

The executive committee reviews and advises the ERC Director on research, administrative, and policy issues of the ERC. The committee consists of the director, assistant director, laboratory manager, thrust area leaders, support group leaders, the dean of the college of engineering, and selected representatives from the college and the ERC. The budget committee consists of the thrust area and support group leaders.

The Industrial Policy Board reviews the ERC's activities and advises the director and the executive committee. In addition, Technical Advisory Boards (one for each thrust area) have been established to participate in setting the direction of the ERC's research. The Industrial Policy Board consists of selected representatives from the industrial partners who represent each of the thrust areas. The Technical Advisory Boards consist of representatives from each of the industrial partners who are interested in the activities of that area. Figure 4 shows an organizational chart of the ERC. To facilitate the development and management of such a cross-disciplinary Center, the director may delegate some of

the responsibilities to the Assistant director, laboratory manager, and/or thrust area and support group leaders.

The ERC has a stated policy that single-investigator and single-discipline projects will not be supported. This policy embodies the mission and goals of the ERC and is supported by our industrial partners. Our advisory boards, as well as all of our industrial partners, review and evaluate research progress and proposals. The Industrial Policy and Technical Advisory Boards are composed of persons with diverse backgrounds to ensure cross-disciplinary integration of ideas and make recommendations to the executive committee concerning inclusion and exclusion of projects. The Technical Advisory Boards meet at least twice during the year and the Industrial Policy Board meets at least three times during the year with additional conference-call meetings. In addition, all projects are discussed at the ERC's midyear review in April, and written evaluations are collected at the ERC's Annual Meeting in December from all of our industrial members. The director makes final project inclusion/exclusion decisions and allocation of funds based on the recommendations by the Budget Committee, the Executive Committee, the Industrial Policy Board, the Technical Advisory Boards, and the written evaluations by our industrial members. Those research projects that exemplify high-quality work and fit with the mission and goals of the ERC will be considered for funding.

The ERC is currently staffed by 29 faculty, 22 academic and postdoctoral staff, 53 graduate students, and 20 undergraduate students. All of these groups maintain major roles in the ERC. The academic staff provide the continuity and expertise needed to sustain the ERC's programs over a considerable period of time. Responsibility for the academic staff resides with the director and the executive committee, and includes salary increases and promotions, and matters related to hiring and retention of the staff. Each academic staff member and postdoctoral fellow is asked to write an annual report describing their activities in detail. This report is used for evaluation purposes for merit-based salary increases and/or promotion.

Since faculty members are part of an academic department in their University, the ERC cannot directly affect the promotion and/or salary determinations. However, cross-disciplinary research efforts and formal joint appointments are now recognized and widely accepted in major research institutions. The ERC Director writes to the Chairs of the academic departments to provide supporting material describing the activities of ERC faculty members. Three faculty members in the ERC have now received tenure partly as a result of their activities in the ERC.

V. CROSS-DISCIPLINARY NATURE

A representation of how cross-disciplinary the Center has become is shown in Fig. 5. Each thrust area and support group is shown in this figure with a breakdown by academic discipline in the categories of faculty, professional staff, graduate, and undergraduate students.

VI. EDUCATIONAL IMPACT

In order for plasma-aided manufacturing to have an impact on the competitiveness of U.S. industry, it will be necessary to have future generations of engineers advance the technology of our field. Through our industrial interactions, we have become aware that there are not enough students trained in the cross-disciplinary approach necessary to ensure the advancement of plasma-aided manufacturing. We are also concerned that engineers in industry today are not aware of the latest developments in the field. Since each thrust area and support group is comprised of students at the undergraduate and graduate levels, these students are exposed to the ERC concept in the course of their activities.

Plasma manufacturing systems tend to be very complex and cross disciplinary, from the standpoint of both the actual plasma-material interactions and the manufacturing systems. Students require training in both aspects of the problem in order to become effective in transferring this technology to industry. It is also clear that training students to follow what has been done in the past is no longer sufficient to advance the field. Rather, students will need to integrate knowledge from many disciplines.

The presence of our ERC has resulted in the development of new courses and laboratories, both at the graduate and undergraduate levels. The cross-disciplinary research groups themselves have already shown major changes in the nature of research topics, many of which could not have been done without the Center's presence. In addition, we strive to develop an outreach program that exposes elementary-, middle-, and high-school students, undergraduate and graduate students at other universities, and returning adult students to science, engineering, and plasma-aided manufacturing. We recognize the importance of educational activities that involve our industrial partners and are working toward developing educational ties with them.

The ERC's weekly seminar series is now videotaped and is made available to our industrial partners and the ERC faculty, staff, and students. Our basic ERC course, *Plasma Processing and Technology*, is offered during each spring semester at Madison. Last year this course was videotaped and made available to our industrial partners. A new course, *Atomic Collisions*, is currently being considered for cross listing among the Electrical and Computer Engineering, Nuclear Engineering and Engineering Physics and the Physics Departments. A new special topics course during the fall 1991-92 academic year entitled *Weakly Ionized Plasmas* adds to the Electrical and Computer Engineering Department's offerings in courses directly related to the ERC. These courses help to expand our classroom contacts.

At the University of Minnesota, a course on plasma-aided manufacturing is being developed at the University of Minnesota to be taught together with the University's Design and Manufacturing Division and will include lectures from industrial representatives. Additionally, plasma-aided manufacturing design concepts have been introduced in traditional courses such as senior design projects.

Table I-1: Faculty, Staff and Student Involvement in Thrust Areas and Support Groups According to Their Department or Discipline¹.

	ChE	Chem	ECE	IE	MSE	Mat Sci	ME	NEEP	Phy	Stats	Env, Tex, & Design	Tech Staff	Total ²
Etching													
Faculty		2	2					3	1				7
Researchers ³		1			1			2					5
Grad. Stud.		1	6		1	3		2					13
Undergrad.			4										4
Dep & Polym													
Faculty	1	1	3	1					1		1		8
Researchers	2		1		1							3	7
Grad. Stud.	2		3			1			1		1		8
Undergrad.	2		3				1		1				7
Thrm. Plasma													
Faculty	1	1	1				5						8
Researchers			1		1		4						6
Grad. Stud.	1						9						10
Undergrad.			1				1		1				3
Plasma Mod.													
Faculty					2			3					5
Researchers					1			3	1				5
Grad. Stud.					3	7		4					14
Undergrad.			1		2		1		1				5
Diagnostics													
Faculty		2	2				1	2					7
Researchers		1					1	2	2			2	8
Grad. Stud.		1	1				1	1					4
Undergrad.													0
Theory/Mod.													
Faculty			2				1	1					4
Researchers								2					2
Grad. Stud.			1			2	1						4
Undergrad.			1										1
Eng. Stats.													
Faculty				1									1
Researchers					1								1
Grad. Stud.				1	1	1		1		2			6
Undergrad.													0
TOTAL⁴													
Faculty	2	4	6	1	2		5	6	1		1		28
Researchers	2	1	2		3		4	6	3			3	24
Grad. Stud.	3	1	9	1	5	12	9	6	1	2	1		50
Undergrad.	2		8		2		3		3				18

¹ ChE=Dept. of Chemical Engineering or Dept. of Chemical Engineering and Material Science
 Chem=Dept. of Chemistry
 ECE=Dept. of Electrical and Computer Eng.
 IE=Dept. of Industrial Engineering
 MSE=Dept. of Materials Science and Engineering

Mat. Sci.=Materials Science Program
 ME=Dept. of Mechanical Engineering
 NEEP=Dept. of Nuclear Eng. and Eng. Physics
 Phy=Dept. of Physics
 Stats=Dept. of Statistics
 Tech Staff=Engineering Research Center Technical Staff
 Env, Tex, & Design= Dept. of Environment, Textiles, and Design

² The rows in this chart are additive as shown in the "Total" column.

³ Researchers include post-doctoral staff and academic staff.

⁴ The columns in this chart are not additive as shown in the "TOTAL" row since one person may be in more than one Thrust Area or Support Group. The "TOTAL" row represents the entire ERC.

Fig. 5. ERC personnel organized by academic discipline in thrust areas and support groups.

A new undergraduate laboratory entitled *Statistical Experimental Design Laboratory Plasma-Aided Manufacturing* has been developed. This laboratory, which is proposed for cross listing among the Departments of Chemical Engineering, Electrical and Computer Engineering, Industrial Engineering, Materials Science and Engineering, and Mechanical Engineering is the first undergraduate experimental laboratory of its kind, which will introduce statistical experimental design in a "hands-on" environment. In this way, we expect that our systems view of statistical experimental design will become integrated in the curriculum

of the participating departments. We view this as the first step in helping undergraduate students to develop an understanding of the role that practicing engineers have in industry.

Since our ERC is a "two-site" activity at both the University of Wisconsin-Madison and the University of Minnesota and because communication among faculty, staff, and students in the entire ERC is of paramount importance, we bring all the faculty, staff and students together on a regular basis to present and discuss each student's research activities.

The ERC staff and student research book, which describes the individual staff and students and their research projects and interests, was initiated last year and is now being updated. It is distributed to all of our industrial partners and to the ERC's faculty, staff, and students to further develop cross-disciplinary communication and to stimulate direct contact between ERC participants and industrial representatives. Our summer intern program places 10-15 ERC undergraduate and graduate students, staff, and faculty at industrial sites.

To encourage precollege students to enter the field of science or engineering, we are conducting and planning several activities at the elementary through high-school level. At the elementary-school level, the ERC will again be participating in the University of Wisconsin-Madison's "College for Kids" program this summer. The program brings students from local elementary schools to the University of Wisconsin-Madison to spend three weeks with ERC faculty and staff learning about two fields of study and participating in hands-on experiments.

For high-school-level students, a team of University of Wisconsin Society of Women Engineers undergraduates makes a presentation on science, engineering, and plasma-aided manufacturing to high-school chemistry, physics, and mathematics students. These programs will be expanded in the future to include middle schools and other high schools in the region. The ERC also holds a "Saturday Enrichment Program" for middle-school students entitled "Plasmas, Electricity and Electronic Measurements." The course was open to students in grades 5-8 who were interested in the subject. The course was full; 15 students participated by coming to the ERC for class every Saturday for six weeks. A new project in interactive computing software using plasmas is now underway and being field tested in the K-12 grades.

A microfabrication demonstration kit to be used as a teaching tool in K-12 education has been developed in conjunction with AAAS Project 2061: Science for All Americans. The objective of Project 2061 is to revamp the K-12 science and engineering curriculum in the United States. The microfabrication kit is being disseminated with the aid of the Lawrence Hall of Science at the University of California-Berkeley and the Institute for Chemical Education (ICE) at University of Wisconsin-Madison. The kit consists of a fully processed silicon wafer, an electronic circuit board, a microfabrication mask, packaged chips, and a set of overhead transparencies for classroom use. The materials for the kit were donated by our industrial partners, and the University of Wisconsin-Madison. Approximately 100 kits have been distributed to date in more than 30 states. The pedagogical objectives are to stimulate student interest in science and technology and to provide teachers with a starting point for activities in electronics. In phase 2, the kit will contain hands-on projects that students can build to illustrate the fundamental notions of logic circuits. A presentation about the kit was given at the National Science Teachers' Association Annual Meeting in Houston in March 1991. The talk was given to the members of Science 4

Science Teachers (S4ST). This is a program administered through the Lawrence Hall of Science and is made up of middle-school teachers from around the country.

During April 1991, the ERC participated in the biennial Engineering Exposition at the University of Wisconsin-Madison. During the three days of the exposition, more than 20 000 visitors toured the ERC's laboratories and saw plasmas being used to deposit materials on surfaces, viewed plasma products, and learned about the ERC concept. In addition, the ERC participated in the Research Fair which is a similar event at the University of Minnesota.

During June and July, 1991, the ERC hosted six students who each participated in a research project for eight weeks as part of the NSF's ERC Research Experiences for Undergraduates (REU) program. Six undergraduate students from a number of colleges and universities will be joining in the ERC's research activities for eight weeks. In addition, the ERC, together with the Society of Women Engineers (SWE) and the Wisconsin Black Engineering Student Society (WBESS), holds two special competitions for undergraduates each year. The winners of these competitions become ERC undergraduate interns. In the 1990-91 academic year, we selected three SWE and one WBESS candidate to receive internships. During the summer of 1991, one of the SWE interns will be participating in our industrial summer intern program as well. The ERC has also established a summer internship for faculty of the Madison Area Technical College who are involved in the education of students pursuing careers in technical fields related to plasma-aided manufacturing. By becoming familiar with plasma-aided manufacturing, we envision that these faculty members will be better able to ensure a supply of technically trained personnel for this field.

For continuing adult education and community service, several short courses on thermal plasma processing are being presented to industry. These courses were offered in conjunction with the Materials Research Society Meeting (April 1990) and the Plasma Spray Conference (May 1990). In April 1991, the ERC, together with the Department of Engineering Professional Development, made available to its industrial partners the short course *Designing Industrial Experiments: The Engineers Key to Quality*.

The education activities of our ERC are important and growing. To ensure that this will continue, the ERC has now established an Education Committee composed of faculty and administrators from within and outside of the ERC to coordinate and integrate the ERC's educational mission.

VII. PROCESS AND IMPACT OF INDUSTRIAL INVOLVEMENT

Our ERC has a unique position in that plasma technology is very widespread throughout a broad cross section of industry. However, in many cases, it is often not the major part of a particular company's business. As a result, present and potential industrial users of plasma technology often forego its development unless it is the only way that a particular manufacturing step can be accomplished or it can be shown to be more economical than competing

technology. It is our belief that this situation requires us to make our industrial partners continuously aware of our results and to develop new methods of joint collaborative activity.

We achieve this in the following ways. First, at least three times per year—at our annual meeting, our midyear review and our NSF site visit industrial partners have the opportunity to send representatives to the Center to receive a broad overview of all our activities. Each thrust area also has a Technical Advisory Board consisting of all interested industrial partners. These Technical Advisory Boards meet throughout the year, often in conjunction with Center review functions. Industrial representatives also visit the Center on an individual basis, often presenting a seminar to the ERC personnel.

The best means of transferring technology is by moving people. As a producer of students, universities are natural suppliers of this form of technology transfer. We and our industrial partners have benefitted greatly by their hiring of our graduates, since we have already established good working relationships with them. In fact, one of our graduates has recently been named by an industrial partner as a key contact person with our ERC.

Technology transfer to industry requires a continuous interaction between our partners and ourselves. Our goal is to develop our technology to the point where industry can "take it over." As a particular example of this, one industrial partner is constructing a plasma source ion implantation chamber at their Technical Center, and has been working directly with ERC personnel from the outset. Thrust area 2 has developed three new projects, ECR deposition, barrier coatings, and treatment of fibrous materials. These projects have drawn a great deal of interest from our industrial partners. Thrust area 3 has established more industrial interactions and development of specific technology transfer activities are under way. Thrust area 4 has joint research and technology transfer activities with more than a dozen industrial partners. Thrust area 1 has submitted research proposals to a number of ERC member companies and has received a considerable amount of equipment donations and several industrial members have spent or will be spending extended visits at the ERC.

We have developed a number of methods to increase our involvement with industry. First, we now offer an expanded membership to our industrial partners, which carries with it some intellectual property rights. Second, we have now provided a financial incentive for faculty to secure outside support from our industrial partners for contract research. During the current year, 10% of the budget of each thrust area and support group is escrowed by the Center. These funds are released to each thrust area and support group on a dollar-for-dollar matching basis, up to the 10% level, when contracts are established with an ERC industrial partner. In subsequent years, we will evaluate the effectiveness of this escrow policy as an alternative to increasing the base membership fee. As our Center evolves, we anticipate that technology transfer issues will require more attention. In planning for this time,

we have designated a person to serve as ERC technology transfer manager. This person works with both industries as well as other organizations that may act as agents of technology transfer. The day-to-day activities of the coordinator would involve meeting with companies, either on campus or at their sites, meeting with faculty and students in the ERC, and meeting with third party "agents" for technology transfer, such as officials of the Wisconsin Technology Development fund. The technology transfer coordinator will prepare plans for specific activities where a good match between need and opportunity is found and seek new options for technology transfer.

VIII. ERC RESEARCH IN THE THRUST AREAS

This section describes a number of research results in each thrust area, in more detail, placing particular emphasis on the unique features of the ERC which make such research possible.

A. Thrust Area 1—Plasma Etching and Microwave Processing for Microelectronics [13]-[37]

The overall goals of thrust area 1 are: 1) to bring together a large number of diagnostics and diagnostic techniques for etching plasmas; 2) study conventional and novel etching techniques, such as conventional parallel plate reactive ion etching (RIE), microwave electron cyclotron resonance (ECR) etching, multidipole-assisted RF (MRF), and helicon RF; 3) establish the relative advantages of these different etching techniques and how the plasma parameters scale with process control parameters; and 4) develop control strategies and techniques for etching. Figure 6 shows thrust area 1's five-year plan.

The strategy of thrust area 1 is to cluster as many diagnostics as possible at each type of tool so that the plasma parameters are overdetermined in the sense that more than one diagnostic will provide overlapping data. The diagnostics that are currently operational in the etching area (and coordinated by the diagnostic support group), are Langmuir probes (both collecting and emitting), laser induced fluorescence (LIF), infrared absorption (IR), visible and vacuum ultraviolet (VUV) emission, and quadrupole mass spectrometry (QMS). A new type of measurement device, a pitch-angle diagnostic (PAD), is under development. In addition, a He-Ne laser interferometer is being employed in the RIE system for in situ etch rate measurements and feedback control.

In our study of conventional and novel etching tools, our approach has been two-fold: 1) establish the scaling of plasma parameters (e.g., ion densities and energies, electron temperatures, radical concentrations, etc.) with process control parameters (e.g., power, pressure, gas composition, flow rate, etc.); and 2) compare the relative advantages and disadvantages of our three-etching tools. Langmuir probe measurements are being made in all three systems under various process conditions to measure plasma potentials, ion densities, and electron temperatures. LIF measurements in the ECR system have yielded information on ion ve-

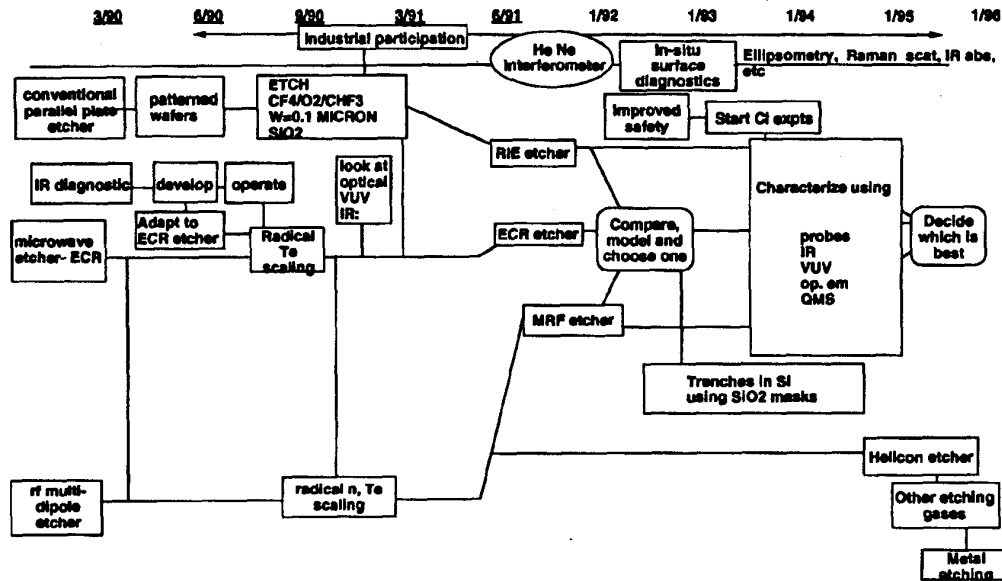


Fig. 6. Five-year plan for thrust area 1.

CF₂ Densities in 50% CF₄/50% CHF₃ Plasmas

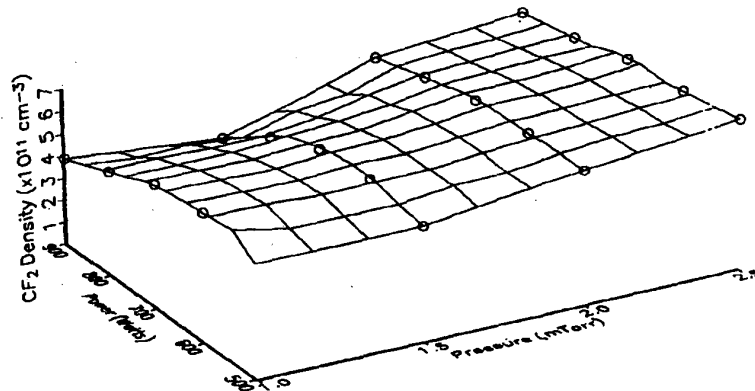


Fig. 7. CF₂ concentration in an ECR reactor.

locities both parallel and perpendicular to the axis of the system. Infrared absorption is being used to determine the absolute and relative densities of free radicals in the plasma. Several radicals in the ECR system, such as CF₂ and C₂F₆, have already been studied and work is continuing to establish how these radical concentrations scale with the process control parameters. The measurements of CF₂ concentration in an ECR reactor for various plasma conditions are shown in Fig. 7.

Visible optical emission and QMS are easily portable diagnostics and therefore are employed on all three systems as needed. The MRF system has served as the primary test bed to the VUV emission measurements. While many of these measurements have already yielded valuable data, we will continue applying these diagnostics to our three-etching

systems to obtain more complete data on the scaling of plasma parameters with process parameters and to elucidate the relative advantages and disadvantages of the three systems. Results from the Theory and Modeling Support Group will also be used in our evaluations.

As part of our effort to investigate the scaling of the different etching techniques and to compare them, we are looking at how actual etching results relate to results from our numerous diagnostics measurements. In particular, we wish to look at how etch profile, etch rate, selectivity, and linewidth reproduction correlate with plasma parameters. A prerequisite to these experiments is the generation of wafers patterned with an appropriate photoresist mask. We have the capability to generate these photoresist patterned wafers at both the Center for X-ray Lithography (CXrL) and the Wis-

consin Center for Applied Microelectronics (WCAM). The facilities at CXrL are employed for submicron linewidth generation. Experiments aimed at investigating the integrity of the X-ray resists during plasma etching in the RIE system are in progress. Future experiments will be aimed at etching and maintaining the narrow linewidths obtained from X-ray lithography. Photoresist processing experiments with conventional photoresists are also in progress at the WCAM for linewidths greater than 1.5 microns. While the current photoresist process available in the WCAM does not generate ideal line profiles, the process is sufficient for our etch rate and selectivity studies on our various etching tools. We also benefit from the donation of wafers by our industrial partners. The RIE system serves as our benchmark system, providing a baseline for comparison among the three tools. For our initial etching experiments we have chosen to etch silicon dioxide with $\text{CF}_4/\text{O}_2/\text{CHF}_3$ gas mixtures. Future studies will be aimed at either silicon or metal etching with chlorine-based chemistries.

Our fourth overall goal to develop control strategies and techniques is also being addressed. Some feedback control studies have been conducted on the RIE system using the *in situ* etch rate measurement from the laser interferometer as the process monitor. Future studies are planned using feedback from mass spectrometry and optical emission as the process monitor. Attempts will be made to implement the less complex diagnostics, such as visible and VUV emission and QMS, in industrial settings.

After evaluating the relative advantages and disadvantages of the RIE, ECR, and MRF etching tools, it should be possible (by the fourth year) to devote considerable effort to new techniques such as helicon and inductive plasma sources. Initial studies of such techniques are planned for the near future. Other novel diagnostics, such as microwave interferometry, VUV LIF, ellipsometry, or *in situ* surface diagnostics, will be phased in, if time and budgetary constraints permit.

B. Thrust Area 2—Plasma Deposition and Polymerization [38]–[50]

Thrust area 2 focuses on the plasma deposition of polymeric films, silicon compounds and the surface modification of polymeric materials. The goal of thrust area 2 is to develop the diagnostics, modeling and control techniques necessary to use these processes effectively in industry. This thrust area has a very large number of potential applications and as a result, although it is necessary to emphasize only a nominal number of processes, we believe that the techniques we are implementing will have applications to a wide variety of plasma deposition processes. A new parallel-plate 13-MHz reactor called the parallel-plate plasma polymerization (P4) will become the engineering test bed for a number of these. P4 has been designed to ensure compatibility with the diagnostic tools being developed in the ERC. It is also computer controlled to facilitate real-time control of the deposition process and the acquisition of diagnostic data. The current material under

test in this system is polymethylmethacrylate (PMMA). This material is deposited on silicon substrates that can either be coated with a conducting or insulating film or be uncoated. The deposition pressure is approximately 100 mTorr. Subsequent modifications to the reactor will include the use of ECR, RF induction, and/or magnetically confined plasma sources.

Several additional projects have been suggested by our industrial partners. These include the deposition of silicon-containing compounds, the deposition of barrier coatings for polymer materials and plasma treatment of fibrous materials. Should funds be made available, thrust area 2 will expand in these directions.

The research objectives of thrust area 2 are:

- 1) optimize plasma deposition and/or polymerization process parameters with respect to key material properties such as dielectric permittivity as a function of wavelength, residual stress and adhesion to a variety of surfaces;
- 2) understand the relationship between plasma parameters and the material properties listed in (1);
- 3) develop a model for the plasma kinetics of the polymerization process; and
- 4) investigate applications using the plasma-deposited films. These include a deep UV PPMMA conformal photoresist for three-dimensional applications, the fabrication of polymer channel waveguides having graded index behavior along the potential applications for barrier coatings deposited on the inside or outside of hollow shapes and the use of less harmful substitute materials for deposition of silicon-containing compounds.

The five-year plan for thrust area 2 is shown in Fig. 8. Recent accomplishments of thrust area 2 are:

- 1) the design and fabrication of a new 13.5-MHz parallel plate reactor system optimized for use with diagnostic tools;
- 2) the optimization of the plasma deposition of PMMA for use as a deep UV photoresist using statistically designed experiments;
- 3) PPMMA films having a thickness uniformity of 5% over a 4-in. wafer are deposited at a rate of up to 700 Å/min. The refractive index in the visible can be varied over the range of 1.52–1.62 by varying the RF power during film deposition. The resolution of the deep UV photoresist is better than 1.5 μm at 250 nm; and
- 4) the beginning of a collaboration with industrial partners on the measurement of residual stress in PPMMA films.

The variation of the index of refraction of PPMMA that can be achieved as a function of RF power for red, green, and blue light is shown in Fig. 9.

The following material describes the activities for thrust area 2 in more detail showing how the ERC environment has directly affected the nature of the research to be performed.

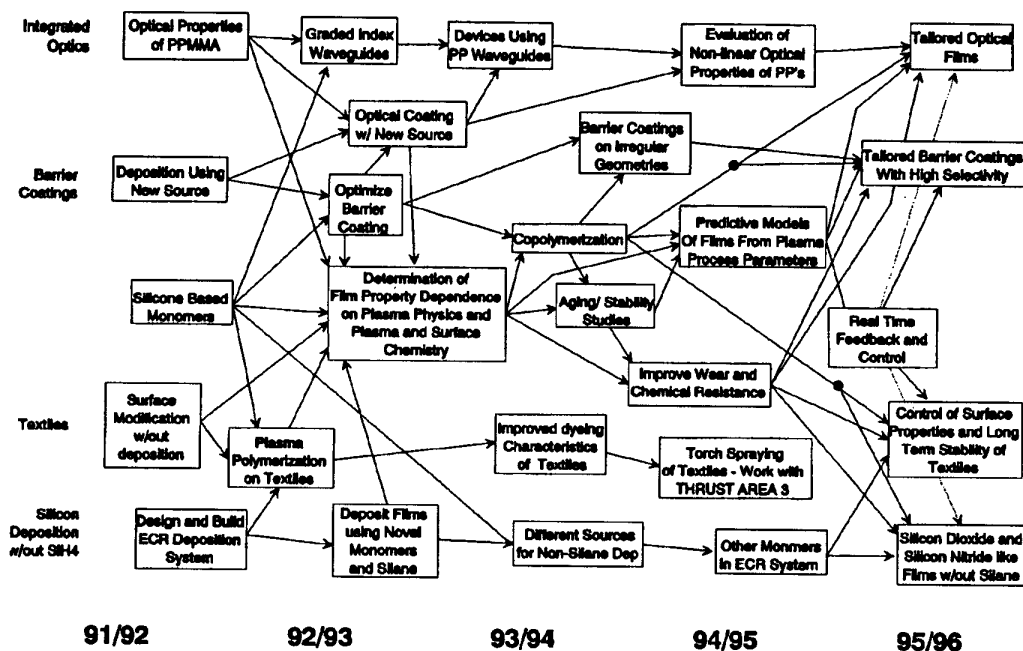


Fig. 8. Five-year plan for thrust area 2.

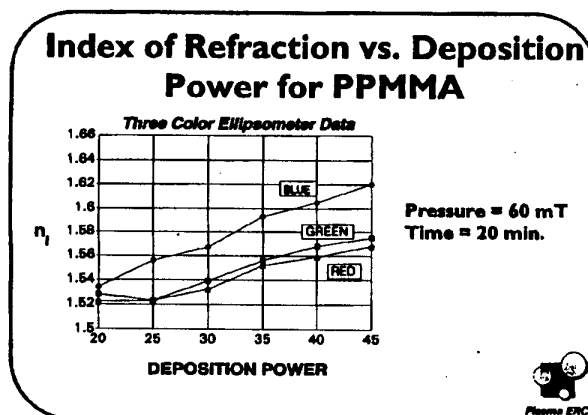


Fig. 9. Variation of the index of refraction of PPMMA-deposited films as a function of RF power.

1) **Plasma Polymerization:** The new 13.56-MHz parallel plate deposition reactor is being outfitted with a PC-based controller so that automated deposition processes will be possible. This will facilitate the statistical experiments and the use of statistical process control. In addition, now that we have a stable baseline process, we are in a position to begin to use diagnostics to monitor plasma parameters. These diagnostics include Langmuir probes, optical emission spectroscopy, laser-induced fluorescence, and possibly mass spectrometry. These will allow the determination of electron temperatures and densities, reactive species present and their concentrations, and plasma potential. These data will be used in conjunction with the plasma modeling

effort to help understand the plasma kinetics and the surface and growth kinetics of the plasma polymer. The modeling effort uses a particle-in-cell approach to model plasma kinetics. As the diagnostic tools come on line, statistical techniques will be used to determine how the plasma process parameters (such as power, flow rate, and pressure) are related to the internal plasma parameters (such as electron density and temperature) and how the plasma process parameters are related to the desired materials properties (such as refractive index, dielectric behavior, and residual stress). Given this information, it will be possible to tailor the materials properties of the deposited polymer films. In particular, we plan to fabricate polymer

channel waveguides with graded indices of refraction for waveshaping applications in photonics. In order to achieve this goal, we need to deposit films on the order of 5–10 μ in thickness. This will require that the deposited films have minimal residual stress. A major research goal is to use statistics, diagnostics, and modeling tools to develop a mechanistic model for residual stress in PPMMA films.

2) *ECR Deposition:* This activity is a collaborative effort between the ERC and several industrial partners. We plan to optimize the deposition process in order to insure the desired materials properties of deposited films. The materials systems of interest are alternate vapor sources for the deposition of silicon compounds. The source most frequently used now, silane, presents safety hazards as it is explosive when exposed to ambient air. We plan to use a low temperature ECR deposition system in this phase of the work. ECR has a number of promising advantages for deposition and we expect to determine and optimize its effectiveness by use of the diagnostics and modeling methods made available through the Center.

One industrial partner will provide the ERC with a number of novel liquid-vapor sources to use as silane gas substitutes in the ECR deposition of silicon nitride, which is of great interest to semiconductor manufacturers. The ERC diagnostics will be used to develop an understanding of the nitride deposition process. In particular, as the chemical kinetics are understood, we expect to interact with our industrial colleagues to design more advanced molecules which will minimize unwanted free-radical composition. The deposited films will be characterized using facilities available on campus. The chemical composition will be investigated using Auger and ESCA. The refractive index in the visible will be measured using a three-color ellipsometer and the dielectric behavior will be characterized using a parameter-analyzer system available to the ERC. Another industrial partner will concurrently deposit nitride films using silane gas mixtures in an ECR reactor. These films will be characterized there and the properties will be compared to those deposited with the alternative sources.

3) *Plasma-Deposited Barrier Coatings:* Several of our industrial partners have expressed an interest in developing plasma deposition sources and processes for surface-selective deposition of barrier coatings in or on forms of varying shape and scale. Barrier coatings are required on certain containers to prevent the permeation of gases such as oxygen through container walls or to prevent the escape of vapors out of the container. In certain cases, plasma-deposited coatings have either a processing or a performance advantage over conventional methods such as coextrusion and wet or gas chemical deposition. As an example, plasma-deposited polymer coatings are highly cross linked, and the deposition process does not produce substantial amounts of chemical waste as does a wet chemistry process. Unfortunately, however, many plasma source systems do not physically deposit coatings that conform to the odd shapes of tubes, bottles, and other hollow and reentrant forms.

We plan to investigate plasma deposition of barrier coatings with several RF capacitive and inductive plasma sources. Working with our industrial partners, we will apply our expertise in plasma engineering to design sources and processes directed toward a number of contemporary manufacturing goals. Our activities will draw from nearly every facility and support group within the ERC. Plasma source design and construction will require RF electromagnetic field modeling, 2-D plasma modeling, and much of the Center's plasma diagnostic capabilities, such as electric probes, optical-emission spectroscopy, IR spectroscopy, and mass spectrometry. Process development will require film characterization studies, statistical experimental design, and testing of surface-barrier aging and performance. By placing the source design directly within the context of our partners' industrial applications, we will ensure the transfer of technology and engineering advances.

4) *Plasma Modification of Fibrous Material:* The goal of this work is the modification of surface characteristics of textiles and composites, while leaving their bulk properties and appearance unaffected. By controlling the composition of the plasma, the surface of the polymer can be tailored for a specific end use. Previous work has been done on improving the interfacial bonding properties of carbon, kevlar, glass, polyethylene, polyester and other thermoplastic fibers.

The primary direction to be followed here is to improve the surface characteristics of fibrous materials (textile materials and composites) for wettability (both hydrophilicity and hydrophobicity), static and soil resistance, printing and dyeability. Compared to other treatments plasma processing offers the following potential advantages: lower cost, lower total energy consumption, less required space, more rapid treatment, decrease in process liquids, higher reproducibility, and less toxicity.

The project will compare the properties of plasma, chemically treated, and untreated materials. Their surface and chemical and aging properties will be measured and compared using the diagnostics available in the ERC. Engineering statistics will be used to optimize the plasma process. The common plasma diagnostics and modeling developed for all of the projects in the deposition and polymerization area will be employed to determine the plasma properties required for effective treatment. Subsequently, we will examine the feasibility of scaling up the process to a manufacturing environment.

C. Thrust Area 3—Plasma Synthesis, Sintering, and Spraying [51]–[64]

This thrust area is divided into three projects: 1) plasma spraying, 2) thermal plasma chemical vapor deposition (TPCVD), and 3) plasma sintering. The long range goals for thrust area 3 are: 1) plasma spraying: to develop design guidelines for plasma spray coating equipment and to implement process controls to assure reproducible coating quality, both within the framework of establishing plasma spraying as an economical manufacturing technology; 2) thermal plasma CVD: to determine the set of process

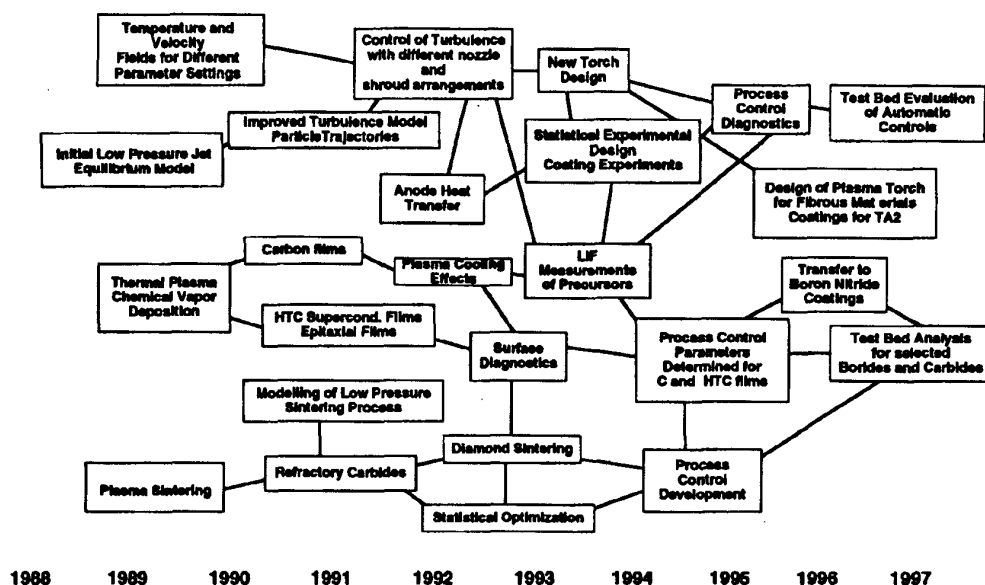


Fig. 10. Five-year plan for thrust area 3.

parameters which will assure deposition of CVD quality or even epitaxial coatings at rates exceeding 10 microns per hour, thus laying the foundation for commercial TPCVD process and equipment development; and 3) plasma sintering: to demonstrate the technical viability of this technology as an industrial process. The strategic plan for thrust area 3 is shown in Fig. 10.

D. Approach

1) *Plasma Spraying*: A three-pronged approach will be followed by advancing the knowledge base through diagnostics and modeling of the plasma-particle interaction and of the dependence of plasma jet fluid dynamics on the spray-nozzle design; enhancing the technology base by obtaining empirical correlations between coating characteristics and spray process parameters using statistical experimental design methodology; and by making use of any advances in our understanding through testing of equipment and/or process improvements. The characterization of the plasma jet of a commercial plasma spray gun has been extended to Mach 1 operating conditions. We are now able to put together an overall "picture" of the flow structure in a thermal plasma jet: an initially laminar core surrounded by a turbulent boundary layer becomes unstable due to the untrainment of large cold gas vortices that initially coalesce in the jet fringes and eventually penetrate into the central portions of the jet. Based on this analysis, the ERC-developed hot anode gas shielded (HAGS) plasma torch is designed to improve the operation of thermal plasma jets. It is shown in Fig. 11. The HAGS torch has a higher power efficiency than a conventional DC torch of similar design. Full implementation of the HAGS torch will result in more

efficient use of electrical power, improved coating quality, and more rapid coating deposition rates.

2) *Thermal Plasma Chemical Vapor Deposition (TPCVD)*: This offers the potential of filling the gap between high-deposition-rate plasma spraying and low-deposition-rate high-quality film growth. Its goal is to extend high-rate coating processes to higher quality films and to provide the base for introducing this technology in manufacturing. Since this process is a vapor-phase deposition processes, materials without a liquid phase, such as diamond and carbides, can be deposition with very high film densities. Our focus in this new technology is on obtaining a detailed understanding of selected processes that have both immediate industrial interest and specific diagnostic value. We have chosen for this purpose high-rate deposition of diamond film, high Tc superconducting films, and nonoxide ceramic films such as SiC and BN. The specific objectives are to identify the most important process-control parameters influencing the film quality and devising guidelines for equipment and process control designs. Four parallel efforts are being pursued: 1) characterization of the plasma and the precursors using modeling and diagnostics, 2) the development of suitable film characterization methods, 3) empirical development of processes using statistical experimental design, and 4) the development of predictive models for TPCVD processes.

3) *Plasma Sintering*: The goal of this project is the implementation of a rapid sintering process that makes use of process enhancements through plasma efforts. A knowledge base has been established including results of modeling and diagnostics of the process. Plasma gas composition, pressure, and powder processing history have revealed the strongest influence on the sintered densities of the

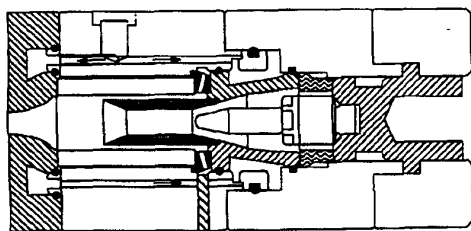


Fig. 11. The HAGS plasma torch.

specimens. Modeling of the sintering processes, which includes a description of the RF plasma and the plasma heat transfer process, have indicated the importance of chemical reactions (recombination) at the sample surface at reduced pressures. Different types of yttria-stabilized zirconia compacts have been successfully sintered at various pressures ranging from 1 to 760 torr, with plasmas produced in pure argon, argon-helium, argon-hydrogen, argon-nitrogen, argon-oxygen, and argon-water vapors. Densities up to 98% of the theoretical density have been achieved in 2–3 min. The microstructures of the sintered sol-gel powder compacts have shown very little grain growth, which is one of the major advantages of the rapid plasma sintering process. Further developments will focus on specific materials of interest to industrial members, such as sintering of HfC or diamond powders.

In particular, hafnium is of significance because it is a high-temperature material with excellent oxidation resistance at elevated temperatures. It can be used, for example, as arc cathodes in oxidizing environments. However, its preparation is very difficult, and a powder metallurgical process would be very advantageous. By introducing hafnium powder into hollow graphite rods, which are then inserted into an RF plasma, sufficiently high temperatures were reached to allow the sintering of the material.

The strong interaction between the efforts within each of the projects is shown in Fig. 10. The different projects within this thrust area are linked by the common base in modeling and diagnostics and basic plasma technology. The linkage with other thrust areas occurs mainly through shared modeling and diagnostics expertise. Our interaction with industry will strongly increase within the third year of this plan when specific results are expected to be transferred to industrial partners. This technology transfer will continue during the following years in all three project areas, while we expect that new developments will appear that promise further enhancement of thermal plasma technology in manufacturing.

E. Thrust Area 4—Plasma Modification of Materials [65]–[73]

The goal of thrust area 4 is the development of new, cost-effective ion implantation techniques for improving the surface properties of materials. In particular, Thrust area 4 is developing plasma source ion implantation (PSII), a patented nonlinear of sight technique for ion implantation

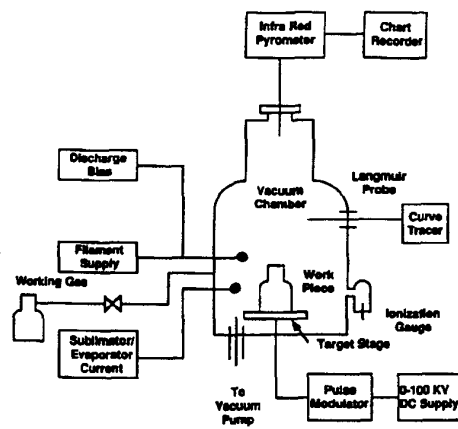


Fig. 12. PSII system.

of surfaces to improve the wear, corrosion, hardness, and fatigue properties of materials. A diagram of a PSII reactor is shown in Fig. 12.

The ERC has identified two subtask areas for the development of methods for plasma modification of materials: 1) surface hardening and wear resistance, and 2) corrosion and oxidation resistance. Preliminary testing has demonstrated that implantation of nitrogen ions by PSII can substantially improve the surface hardness and wear resistance of certain materials in certain environments, but the applications are quite limited. Nitrogen ion implantation is generally effective in increasing the surface hardness and wear resistance for steels with high chromium content in wear applications at low to moderate temperature. Thus, while some of the materials problems of industrial interest are amenable to nitrogen implantation with the present PSII facility, the facility is unable to produce implantation processes that address applications such as: 1) surface hardness and wear resistance of low-chromium steels, 2) surface hardness and wear resistance of ceramics and other nonsteels, 3) hardness and wear in high-temperature environments, 4) corrosion resistance, and 5) oxidation resistance. For these broader applications, ion species such as titanium, carbon, chromium, etc., will be required. To address these problems, we will extend the PSII process to operate in a molecular ion species mode, and modes similar to the ion beam enhanced deposition (IBED) or ion beam-mixing techniques that have been developed using conventional technology. In these latter techniques, a thin layer of a desired nongaseous implant species such as titanium is deposited onto the target (for example by sputter or physical vapor deposition), and then bombarded with energetic ions (for example, nitrogen or noble gas ions).

The attached timetable shown in Fig. 13 outlines our strategic plans for implementation, development, and application of the molecular-plasma species PSII, PSII-IBED, and PSII-ion-mixing processes. We treat three classes of targets: laboratory test coupon specimens, manufactured components, and manufacturing tools. The test coupons are characterized by AES, TEM, SEM, SAM, RBS, ESCA, as

and a better understanding will be required for the IBED development. Another diagnostic need is a noninvasive technique to complement the probe measurements of sheath propagation. To address these needs, we are interacting with the ERC diagnostics support group to measure the ion species composition of the PSII plasma species, and to operate the newly installed laser-induced fluorescence (LIF) diagnostic on the new PSII system.

Besides analytic modeling, we are continuing the development of detailed plasma simulation codes. In this area, we are collaborating with the ERC theory and modeling support group. One code being developed uses the propagator (or Green's function) solution of the plasma kinetic equation. The program includes all the relevant atomic physics as well as electron emission at the target and the chamber wall. The first implementation of the program will most likely be for a helium plasma followed by versions for nitrogen and other plasmas.

Another code is now capable of predicting the energy spectrum of bombarding ions. In the coming year we will compare these predictions with experimental measurements of two types: indirectly, by *ex situ* Auger profiling of silicon wafer test coupons, and directly, using a telemetered energy analyzer inside a model target. We also developing 2-D and 3-D codes to model PSII treatment of targets. As these codes evolve, they will be compared with 2-D and 3-D measurements that are just now beginning to yield results.

IX. SEMICONDUCTOR APPLICATIONS OF PSII

Although PSII was originally conceived as an ion implantation process for nonsemiconductor applications, it has been demonstrated by other PSII groups (most notably the three-way collaboration between Applied Materials Corporation, University of California at Berkeley, and Lawrence Berkeley Labs) that there are many very good applications of PSII in semiconductor processing. PSII achieves in a bell-jar type of environment the same ion implantation treatment previously available only with beamline accelerator technology. This opens up the possibility of incorporating the ion implantation process into other processes; e.g., to do in a single chamber both ion implantation and plasma etching. PSII has particular advantages in the intermediate energy range from 1 keV to 20 keV; these energies are not well suited to either plasma etching processes at the low end, nor beamline implanters at the high end. Specific examples of PSII applications that might be attractive include: backside impurity guttering, shallow implants, ion implantation with rapid thermal annealing, and formation of insulating layers of AlN. We include in our strategic plan the shallow implantation of boron in silicon by PSII in the summer of 1991, and then to implant submicron feature wafers etched by thrust area 1 in the spring of 1992.

ACKNOWLEDGMENT

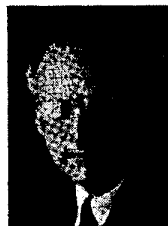
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