A Course on

PLASMA PROCESSING IN INTEGRATED CIRCUIT FABRICATION

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IN THIS PAPER WE review a course entitled "Plasma Processing in Integrated Circuit Fabrication" which was offered for the first time in the spring semester of 1983 at MIT. The course was taught jointly, listed both in chemical engineering and electrical engineering. It has been accepted as a permanent course which will be taught on alternate years.

Plasma processes are playing an ever expanding role in microelectronic fabrication, replacing many of the conventional wet etching and high temperature chemical vapor deposition processes. In very large scale integration (VLSI), plasma processes are required to provide fine spacial resolution and low temperature processing. In most of the plasma processes, the plasma is created by an electric field that accelerates electrons within the plasma. The electrons suffer collisions with gas molecules creating excited neutrals, free radicals, and ions. In this manner, energy is supplied to the plasma creating highly reactive species without significantly raising the average temperature of the gas. Microelectronic fabrication processes typically use low pressure plasmas (1-200 Pascals) which are weakly ionized (less than 10^{-4} mole fraction). They are more appropriately referred to as glow discharges rather than plasmas, due to the non-equilibrium between the electrons, ions, and neutrals from which they are composed. The first use of plasmas in integrated circuit fabrication was for sputtering processes which deposit or etch thin films. In a sputtering process, ions created within a plasma are accelerated by an electric field. Upon collision with the electrode, the ions remove or sputter material from the electrode by momentum exchange, etching the surface of the electrode. The sputtered electrode material can be deposited onto the surface of a wafer to form a thin film. By placing wafers on the sputtered electrode, a thin film on the wafer can be etched. A resist material placed selectively on top of the thin film is normally used to mask the ion bombardment inhibiting the etching in the selected areas. In the late 1960's, oxygen discharges were developed to produce atomic oxygen which chemically etches organic photoresist masks. Presently, plasma etching processes use a combination of sputtering and chemical reaction to remove with high resolution, thin films which have been masked with resist. Chemical vapor deposition is a process in which a gas is thermally decomposed at a hot surface to produce a thin solid film. For example, silane can be decomposed at a hot surface to deposit silicon. Plasma assisted chemical vapor deposition (PACVD) processes have been developed which use the highly reactive species created within a plasma to deposit thin films at lower temperatures than are possible with conventional chemical vapor deposition.

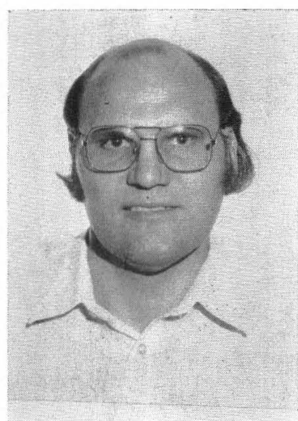
The goal of this course is to teach the fundamental science of plasma processing as well as to give a brief overview of the present state of industrial processes. This goal has a number of motivations. First, we perceive a general lack of understanding within the industrial community with regard to the basics of plasma physics and chemistry. Many of the present plasma process engineers treat plasmas as a "black art" which depends upon intuition and a great deal of trial-and-error. Most of the graduating students going into plasma processing have little or no training, instruction, and/or experience in plasma processing. Also, the plasma physics courses most commonly taught deal with high density, equilibrium plasmas related to fusion reactors.

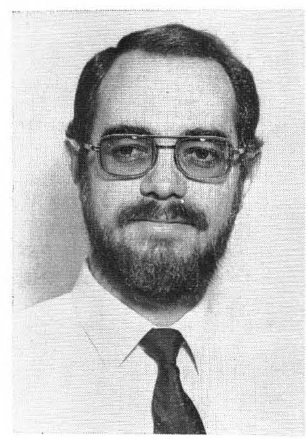
The present engineering state of the art is advancing extremely rapidly with the demands made by the microelectronics industry. We feel that by equipping the students with an understanding of the basics, they will be prepared to make the best use of the advancements. We also feel that an overview of the present use of the plasma processes along with the greater concentration on a few representative areas is best.

In deciding to teach a joint course between electrical and chemical engineering, the advantages and difficulties were carefully weighed. As faculty doing research in the area of integrated circuit fabrication, we have independently taught courses in the more general areas of microelectronic processing in our respective departments. Although there is significant overlap in some of these courses, it is believed that the varied backgrounds of the students in chemical and electrical engineering as well as the different emphasis of the courses more than justified their mutual existence. We saw a need for a more advanced course dealing with the area of plasma processing, a new and rapidly advancing field. It was obvious that this field is highly interdisciplinary and that a pooling of our efforts would create a stronger course than either of us could teach alone. The benefit of having students with varied backgrounds was viewed as more of an asset to the class than a difficulty. The interaction between chemical engineering students who are mostly concerned with how a plasma process functions, and the electrical engineers who are much more aware of the uses of the structures and the subsequent requirements, was thought to be highly beneficial. We decided that a strong emphasis on the engineering science aspects of the processes would form a common background from which both groups would benefit.

As might be expected, no appropriate text could be found which covered all the material we desired. As a text, we chose *Glow Discharge Processes* by Chapman [1], as the most appropriate in its coverage. It is quite readable for the students and formed a basis upon which we built with papers from the literature. *Techniques and Applications of Plasma Chemistry* edited by Hollahan and Bell [2] was also very useful as a reference; in particular, Chapter 1 which deals with the fundamentals of plasma physics and chemistry in glow discharges.

The class had an enrollment of 23 students during the bulk of the course, however, there were typically a number of additional students who sat in on the class depending upon the topic under discussion. Two of the students came from industry to attend the class. We required one homework set per week which accounted for 60 percent of the grade and a term paper which accounted for the remaining 40 per cent. As the term paper deadline approached, the class enrollment took an expected drop to 18 students. The remaining class consisted of 7 chemical engineers, 7 electrical engineers, 3 material scientists, and 1 physicist. We were quite pleased with the overall quality of the term papers and feel that the students benefited by being required to search the literature on the topic of their choice which dealt with plasma processing.





Herb Sawin was born in 1951. He received a Bachelors of Science in chemical engineering from Iowa State University in 1973 and his Ph.D. from the University of California (Berkeley) in 1980. His doctoral dissertation was on the catalytic decomposition of hydrazine using molecular beam scattering. In 1980 he joined the Massachusetts Institute of Technology where he is presently an assistant professor of chemical engineering. He is currently working on the plasma etching of silicon and silicides, the enhancement of surface reactions by ion bombardment, chemical vapor deposition of silicon, and fuel cells. **(L)**

Rafael Reif was born in Venezuela in 1950. He received the degree of Ingeniero Electrico from Universidad de Carabobo, Venezuela, in 1973, and the M.S. and Ph.D. degrees in electrical engineering from Stanford University in 1975 and 1979, respectively. In 1978 he became a Visiting Assistant Professor of electrical engineering at Stanford University, and in 1980 he joined the Massachusetts Institute of Technology, where he is presently an Associate Professor of electrical engineering. He is currently working on the Plasma Enhanced Chemical Vapor Deposition (PECVD) of crystalline silicon films, the PECVD of refractory metals and silicides, the computer simulation of CVD silicon epitaxy, and on low-temperature epitaxial and silicon-on-insulator technologies. **(R)**

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COURSE DESCRIPTION

The first one third of the course covered the basics of glow discharge physics and chemistry. Following the ultra-simplified model for gas kinetics presented in section 1.2 of *Molecular Theory of Gases and Liquids* by Hirschfelder, Curtis, and Bird [3], we quickly developed the gas phase kinetics and transport properties of a neutral gas. Chapman's coverage of this material in Chapters 1 and 2 was too weak in this area to give the student an appropriate physical understanding. Using Hollahan and Bell as a reference, the unique properties of a glow discharge caused by its weakly ionized nature were added to the neutral gas kinetics. The prime emphasis was on the physics of the situation rather than the math and the derivation of the various energy distributions. The significance of the electron energy distribution and how it is related to both the plasma chemistry and the transport properties of the charged species was stressed. Chapters 3 to 5 of Chapman which cover the sheath kinetics, DC discharges, and RF discharges were taught in reasonable detail with some embellishment. We reviewed some of the main probes used to characterize plasmas used for microelectronic fabrication: Langmuir probes [4], optical emission [5], mass spectroscopy, and laser induced fluorescence [6].

Approximately one sixth of the course was spent on sputtering mechanisms and the sputtering processes [7] that have been developed for microelectronic fabrication. Chapter 6 of Chapman was used as background material and was heavily augmented. A very simplified model was used to generate the qualitatively correct results in lecture and in homework assignments. Topics

TABLE 1
Course Syllabus By Lectures

Gas Mechanics: Ideal gas law, energy distributions, mean free path, impingement flux

Gas Kinetics I: Collision cross-sections, energy transfer, ionization, excitation, relaxation

Gas Kinetics II: Completion of lectures

Electron Energy Distribution I: Plasma kinetic theory, transport phenomena

Plasma Chemistry: Plasma chemical reactions, reaction cross-sections, free radical reactions

DC Glow Discharges: Glow architecture, secondary emission, cathode and anode glow

RF Glow Discharges I: RF coupling, glow architecture, voltage distribution

RF Discharges II: Self-biasing, ion bombardment energies, electron energy distributions

Sputtering Kinetics: Sputtering yields, mechanisms, chemical enhancement

Optical Emission: Emission mechanisms, nomenclature, detectors

Laser Induced Fluorescence: Laser probes, mass spectroanalysis, quantification

Other Plasma Probes: Langmuir probes, mass spectrometer, microwaves

Sputter Deposition I: Sputtering physics, DC and RF sputtering, ion beams, magnetron

Sputter Deposition II: Etch rates, masks, profile control, ion beam vs. conventional, mask erosion, redeposition, angular dependence

Overview of Plasma Etching: definitions, wet vs. dry, uses, isotropic vs. anisotropic, selectivity

Etching Apparatus: Parallel plate, reactive ion etching, tunnel, reactive ion beam etching, costs, through-put, wet etch comparison

General Principles of Etching: Volatilization, additives, F and Cl etchants, flow, loading, example of a simple system (O_2 etching of organics)

Review of Si and SiO_2 etching

Aluminum Etching

Etching of Si_3N_4

Plasma Etch Control: Flowrate, power and bias, end-point detection

Plasma Assisted Chemical Vapor Deposition: Overview, equipment considerations, commercial reactors

PACVD of Si_3N_4 and SiO_2

PACVD of Amorphous Si

PACVD of Poly- and Mono- crystalline Si and GaAs

PACVD of Refractory Metals and Silicides

Plasma-Assisted Techniques: Oxidation, nitridation, annealing, ion beam deposition, ionized beam cluster deposition discussed included DC sputtering, RF sputtering, contamination, bias sputtering, triode sputtering, magnetron sputtering, and ion beam technology. Sputtering processes which are capable of producing and controlling multicomponent films were also discussed.

The next one quarter of the class was spent in the discussion of plasma etching. Again, Chapter 7 of Chapman which deals with plasma etching was used as background material and was augmented. Dr. David R. Day, a research associate at MIT, assisted by teaching this section. First of all, the specifications and desirable attributes for good etching processes were outlined. Comparisons were made with wet etching processes that the plasma processes are replacing. Dr. Day chose to concentrate on the etching of carbonaceous materials such as photoresists and polyimides as an example system [8]. He developed an appreciation that etching proceeds by both a chemical reaction and physical sputtering as well as a strong interaction between them. He drew from the literature heavily; outlining the different types of reactors, the volatilization of materials, the use of gas mixtures, and loading in plasma etchers. Anisotropy of etching was discussed on a mechanistic as well as an engineering basis. An overview of some of the more industrially important etching systems was presented: silicon, silicon dioxide, aluminum alloys, silicon nitride, and refractory metal silicides. The aspects of safety, corrosion, and resist degradation were also discussed.

The remaining one quarter of the class was spent covering plasma assisted chemical vapor deposition. First thermally induced chemical vapor deposition was reviewed to build a basis on which the plasma assisted process could be appreciated. The modelling of thermal chemical vapor deposition was presented using classical boundary layer theory and surface kinetics. The need for plasma processes was brought out by reviewing the temperatures which are required for the thermal chemical vapor deposition and the desired deposition processes needed for VLSI. Case studies of silicon nitride, silicon dioxide, polycrystaline silicon, epitaxial silicon, refractory metal silicides, and gallium arsenide deposition processes were discussed.

Because our research work involves plasma processing, we were also able to enhance the class discussion with some of the difficulties we experienced such as pump oil contamination, RF interference, and impedance matching of the plasmas to the RF generators. The presence of a number of students who are presently doing research in the area kept the discussion lively. □

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