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Plasma-Etching Science Meets Technology in the MDL

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Executive Summary

In recent work at Sandia National Laboratories, the results from fundamental investigations of low-temperature plasma systems were used to improve chamber-to-chamber reproducibility and reliability in commercial plasma-etching equipment. This work is an excellent example of how Sandia can make an impact in areas of importance both to national defense and to domestic industry (dual use technologies). It spotlights a unique capability of the Labs in the area of microelectronics: the ability to conduct fundamental research with experimental laboratory equipment and to apply the results of that research to commercial, "in-house" equipment.

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Acknowledgments

This work would not have been possible without the support of many people. We thank Ben Aragon, Dawn Chavez, Mike Cook, Beth Gonzales, Tom Gugliotta, Paul Pochan, and George Roth for their excellent technical assistance. SEMATECH and, in particular, Dick Clover, Ron Horwath and Terry Turner, played an important role in the initiation and funding of this work. We greatly appreciate the encouragement and backing provided by Jim Gerardo and Harry Weaver; they made the whole thing possible. We applaud the Herculean effort of Phil Hargis in the design of the GEC Reference Cell. Thanks also go to Joe Martinez and the Office of Basic Energy Sciences for supporting our fundamental discharge studies under contract KC-03-01-03. This work was performed at Sandia National Laboratories, supported by the U.S. Department of Energy under contract DE-AC04-76DP00789 and by SEMATECH under the SETEC (Semiconductor Equipment Technology Center) program.

Abstract

Results from fundamental investigations of low-temperature plasma systems were used to improve chamber-to-chamber reproducibility and reliability in commercial plasma-etching equipment. The fundamental studies were performed with a GEC RF Reference Cell, a laboratory research system designed to facilitate experimental and theoretical studies of plasma systems. Results and diagnostics from the Reference Cell studies were then applied to analysis and rectification of chamber-to-chamber variability on a commercial, multichamber, plasma reactor. Pertinent results were transferred to industry.

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I. Introduction

One of the most important commercial applications of low-temperature glow discharges is the fabrication of microelectronic circuits. Low-temperature plasmas are indispensable for etching the fine features needed in large-scale device integration. These plasmas are also used to deposit materials, remove photoresist, and enhance oxidation.

Unfortunately, many of the plasma-based processes used to produce integrated circuits suffer reliability problems. A process may work well for some time and then fail mysteriously. A process "recipe" (gas flow, pressure, power, etc.) may yield certain results in one machine and completely different results in another. These types of problems cause decreased efficiency and increased costs for the semiconductor industry.

Optimization and control of the highly complex plasma systems used in the semiconductor industry have been limited by an incomplete understanding of the underlying chemistry and physics of the plasma. Due to its extensive resources, Sandia National Laboratories (SNL) is uniquely situated both to conduct fundamental investigations of the plasma and to apply the results of these studies to commercial processes. SNL has strong diagnostic capabilities (electrical, optical/laser, microwave, etc.) for analyzing plasma systems. In addition, the Microelectronics Development Lab (MDL) at SNL contains a large Class-1 clean-room facility with commercial plasma equipment for semiconductor device fabrication. Unlike the situation in most semiconductor companies, research can be conducted with the full-line equipment in the MDL as well as with experimental laboratory equipment.

In recent projects at SNL, we performed fundamental investigations of plasma systems and used the results of these studies to analyze and rectify problems with commercial plasma-etching equipment. These projects included work supported by SEMATECH and by SNL Organizations 1100 and 1300. Part of this work was conducted as a joint 1100/1300 program. This report summarizes some of these research efforts. In particular, the report concentrates on work conducted to improve chamber-to-chamber (or machine-to-machine) reproducibility and reliability in plasma-etching equipment.

The remainder of this document is divided into three sections. Section II provides background material; it describes a problem encountered with commercial plasma-etching equipment and our approach to rectifying this problem. Section III, in which we present the results of the studies, is a review of a joint 1100/1300 seminar presented in October, 1992. This section contains copies of the overhead transparencies from the presentation along with additional explanatory comments. The final section contains a brief summary.

II. The Problem

The parallel-plate radio-frequency (rf) diode, operating at 13.56 MHz, is the discharge configuration most commonly used for plasma etching. Figure 1 shows a schematic diagram of this configuration.

Fig. 1. Schematic diagram of a parallel-plate plasma-etching system.

The parallel-plate rf diode is characterized by two electrodes that typically are separated by 5 to 40 mm. An impedance matching network couples power from an rf generator to one of the electrodes (in this case, the lower electrode in Fig. 1). The matching network contains a blocking capacitor that prevents the flow of direct current (dc). The other electrode and the remainder of the etching chamber are maintained at ground potential. Due to the asymmetry of the grounded and powered surfaces of the etching chamber and the presence of the blocking capacitor in the matching network, a dc bias develops across the plasma. This bias accelerates positively charged ions toward the powered electrode. If wafers are placed on the powered electrode, highly directional etching can be obtained due to the directional nature of the ion bombardment.

When wafer diameters were small, a number of wafers were placed on the electrode and etched simultaneously. As wafer diameters increased, the semiconductor industry moved to single-wafer processing. A single-wafer processing reactor may have multiple etching chambers with each chamber etching one wafer at a time.

A serious problem, encountered by workers in the MDL and in the US semiconductor industry, is that supposedly identical etching chambers do

not produce the same etch results for a given etch recipe. Not only has this phenomenon been observed for a given model line of etchers from a particular manufacturer, but it has also been observed for different, nominally identical chambers on a multichamber piece of equipment. As an example, two chambers on a Drytek Quad reactor in the MDL are devoted to silicon dioxide etching. For identical input conditions (gas flow, pressure, power, etc.), the etch rates in the two chambers differed by as much as 30%. This performance variability makes process development more difficult and time consuming than necessary. Furthermore, there is another subtle, yet important, implication of process variability for process efficiency. If, in a production line, there is chamber-to-chamber variability, then typically one chamber will produce better overall results than the other chambers. To state it another way, with process variability most of the chambers are inferior in quality of product and/or throughput when compared to the "best" chamber. Therefore, process variability directly signifies inefficiency of the production line.

We investigated chamber-to-chamber variability and discovered solutions for the problem. Our initial studies were conducted with a research plasma chamber known as the "GEC RF Reference Cell."¹ The results from the research chamber were then applied to the Drytek multichamber system in the MDL. The next section of this report details the Reference Cell and Drytek work.

III. Application of GEC Cell Results to Commercial Equipment

As stated earlier, this section, which describes details of the GEC Reference Cell and our results with the Drytek reactor in the MDL, is a summary of a joint 1100/1300 seminar. It includes copies of the overhead transparencies from the talk along with additional comments about the transparencies. The transparencies are presented on the left (even-numbered) pages and the accompanying comments are presented on the opposite (odd-numbered) pages.

¹"The GEC RF Reference Cell: Diagnostic Techniques and Initial Results," K. E. Greenberg, P. J. Hargis, Jr., and P. A. Miller, Sandia Report SETEC 90-013, November, 1990; "The GEC RF Reference Cell: A Parallel-Plate Radio-Frequency System to Study Plasma-Processing Discharges," P. J. Hargis, Jr., et al., Accepted for publication in Rev. Sci. Instruments (1993).

Plasma-Etching Science Meets Technology in the MDL

Ken Greenberg and Paul Miller, 1128
Ray Patteson and Brad Smith, 1324

Outline

1. Background
2. GEC RF Reference Cell
3. Studies of Drytek Quad in MDL
4. Period-doubling & subharmonics
5. Future work

Comments:

This was a particularly exciting project to work on. It is an excellent example of a strength of Sandia Labs: the capability to (1) conduct forefront research, (2) apply the results to commercial equipment and/or processes, and (3) transfer the results to industry. This project stemmed from a fundamental research effort devoted to the study of low-temperature discharge chemistry and physics. The results were applied to commercial plasma-etching equipment in the MDL and were then transferred to the semiconductor industry.

Authors Ken Greenberg and Paul Miller (both in SNL Department 1128) were instrumental in the development of the GEC Reference Cell and, in particular, the Reference Cell diagnostic tool set. Authors Ray Patteson and Brad Smith (both in SNL Department 1324) are in charge of the silicon dioxide and polysilicon plasma etching processes in the MDL. Working together, these researchers applied the Reference Cell results to the commercial equipment in the MDL and then transferred the results to industry.

The following is a brief outline of the work that will be described:

- (1) Background information (acknowledgments, funding support, etc.),
- (2) Details of the GEC Reference Cell and its relevance to this project,
- (3) Application of the Reference Cell results to the commercial equipment in the MDL,
- (4) Period-doubling and subharmonic-generation behavior we observed when using the equipment in the MDL (this behavior arises due to the

- (5) nonlinear nature of the plasma), and
Other work that can be conducted which could be used to improve semiconductor processing both in the MDL and in the semiconductor industry.

Acknowledgements

We received excellent technical support during these studies:

1300 - Dawn Chavez
Mike Cook
Tom Gugliotta
George Roth

1100 - Ben Aragon
Paul Pochan

Financial support was greatly appreciated:
SEMATECH, 1300 (Harry Weaver), 1100 (Jim Gerardo)

Note: The 1100/1300 collaboration could not have been performed five years ago under the production atmosphere required at that time.

Comments:

Many other people were instrumental in the successful completion of this work. Ben Aragon and Paul Pochan (both under contract to SNL Department 1128) participated in the construction, maintenance, and operation of GEC Reference Cells. They also assisted in the development of the hardware and software diagnostic tools used on the Reference Cells and on the commercial equipment in the MDL. Dawn Chavez, Mike Cook, Tom Gugliotta, and George Roth (SNL Departments 1323 and 1324) maintain the Drytek plasma reactor in the MDL; they also participated in the operation of the reactor and in the measurement of wafer etch parameters.

Funding for the Reference Cell and for preliminary MDL studies was provided by SEMATECH, through the SETEC program, and by the US Department of Energy (DOE) through SNL Department 1120. Additional funding for work on the Drytek reactor was provided by DOE through SNL Directorate 1300. We appreciate this support very much.

It should be noted that this joint 1100/1300 collaboration could not have been undertaken as little as five years ago. At that time, the microelectronics fabrication lines at SNL were operated like commercial fabrication lines. Even small, temporary modifications of equipment on the fabrication lines were generally not allowed. Furthermore, programmatic demands for end products precluded use of the fabrication equipment for research. Today, however, usage of the fabrication lines at SNL is more flexible. MDL staff and management are committed to improvement of their equipment and processes and to the use of "in-house" capabilities to accomplish

these goals. This flexibility of the fabrication lines at SNL is a great asset; it provides SNL with the link between fundamental research and technology. SNL is one of the few institutions in the world with complete "in-house" facilities to make this research - to - development - to - application linkage in the area of semiconductor processing.

SEMATECH support rose and fell like a roller coaster

SEMATECH strongly supported the GEC Reference Cell studies and initial Drytek work. Ron Horwath (IBM) and Terry Turner (TI) both championed these studies while on assignment at SEMATECH. They understood that the Reference Cell results would have significant implications for understanding reproducibility and variability problems in plasma etching.

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When Horwath and Turner left, there was no champion at SEMATECH. No new champion emerged even though the SETEC plasma program received the highest marks at the final review and much interest was expressed by the member companies for continuation of the program.

SETEC management failed to elicit new support.

Comments:

While Ron Horwath (International Business Machines) was on assignment at SEMATECH, he was made aware of our efforts on the GEC Reference Cell. He immediately recognized that results of the Reference Cell studies could significantly impact plasma-etching technology. Horwath, along with Terry Turner (Texas Instruments, on assignment at SEMATECH), were very strong supporters of our work and its inclusion in SETEC, the SEMATECH-funded program at SNL. (SETEC = Semiconductor Equipment Technology Center)

Our SETEC plasma project was well received by the staff of the SEMATECH member companies. SEMATECH held annual reviews of the SETEC program at which workers from the member companies rated each SETEC project. The plasma project continually received high marks at the annual reviews and, at the final review, it received the highest overall ratings. Workers from the member companies who attended the final review wanted the plasma work to be continued. By the time of the SETEC final review, however, both Horwath and Turner had completed their assignments and left SEMATECH. (In addition, due to the rapid turnover at SEMATECH, most of the other personnel familiar with our project had left also). Even though workers at the member companies strongly endorsed the plasma work, no proponents remained at SEMATECH. SETEC management failed to elicit new support at SEMATECH and the SETEC plasma project concluded.

When the SETEC plasma project concluded, application of the Reference Cell results to the

commercial equipment in the MDL was in its infancy. We believed that if the work continued, we would be able to improve the performance of the Drytek reactor in the MDL and then transfer the results to industry. MDL management (in particular, Harry Weaver, SNL Department 1321) also felt that this work could improve processing in the MDL and be of benefit to the semiconductor industry. The project continued with SNL funding as a joint 1100/1300 program.

Introduction

The GEC RF Reference Cell was designed for fundamental scientific studies. Workers at Sandia took the lead role in the development of the Reference Cell and in the application of Reference Cell diagnostics/methodologies to the improvement of commercial plasma-etching equipment. Sandia is in a unique position to be able to apply results from fundamental studies to commercial semiconductor processing technologies.

Comments:
This is self-explanatory.

While low-temperature glow discharges have been studied intensively, the investigations have been somewhat "disjointed."

- **Reactor geometry affects experimental measurements**
- **It has been uncertain whether it is meaningful to compare data obtained by different researchers**
- **Discharge model predictions cannot be compared to the wide variety of experimental measurements now available from different research groups**

Comments:

Low-temperature glow discharges have been studied extensively for many years. Unfortunately, it has been difficult to compare experimental data obtained by different research groups because the discharge geometry strongly affects the plasma. Since researchers have typically picked their discharge geometry to accommodate the particular diagnostics they use, it has been unclear as to whether meaningful comparisons could be made for data obtained at different institutions; how similar were the plasmas at the different institutions? Furthermore, it has been difficult to compare results from fundamental discharge models with the wide variety of experimental measurements made in rf systems having different geometries. It seems that it has always been possible to find one set of experimental results that would support the results of any particular model. This has hindered the development of predictive models for rf discharges commonly used to fabricate microelectronic devices.

A reference reactor was developed

1988 Gaseous Electronics Conference (GEC) workshop on
Design, Calibration, and Modeling of RF Plasma Processing Systems

Goals for reference reactor:

- cost effective
- flexible
- good diagnostic access
- technologically relevant

Sandia agreed to generate and distribute engineering drawings for the
"GEC RF Reference Cell".

SEMATECH strongly supported this effort:
hosted meetings in 1989 and 1990 to discuss design and initial data;
included Reference Cell research as part of SETEC.

Comments:

In order to address the problems of data comparison and model validation in rf discharges, Jim Gerardo (then SNL Department 1120) organized a workshop at the 1988 Gaseous Electronics Conference (GEC) entitled "Design, Calibration, and Modeling of RF Plasma Processing Systems." Straw-man designs for a "Reference Cell" were presented by three different groups (including a joint SNL/University of Illinois group). After lively discussions of each design and heated floor exchanges on the need for and/or utility of the Reference Cell concept, general agreement was reached on the desirability of establishing a Reference Cell for measurements in rf-discharge systems of technological importance. It was believed that a Reference Cell could facilitate comparisons of experimental data and model calculations from various laboratories.

An outcome of the 1988 GEC was the establishment of an ad hoc committee, chaired by Phil Hargis (SNL Department 1128). The purpose of the committee, which was composed of both researchers and technologists, was to develop a preliminary Reference Cell design based on ideas generated during the workshop. The committee was charged with determining a cost-effective design for a system that (1) was easy to duplicate, (2) would accommodate a variety of diagnostics, and (3) was technologically relevant. Sandia representatives agreed to develop engineering drawings based on the preliminary design and to make the drawings freely available to all interested research groups. Thus the GEC RF Reference Cell was born.

Ron Horwath and Terry Turner strongly supported

this work at SEMATECH. SEMATECH hosted a meeting on March 9, 1989, in Austin, to bring together members of the ad hoc committee as well as representatives from American Telephone & Telegraph (AT&T), National Institute of Standards and Technology (NIST), and SNL to discuss the Reference Cell design. Participants resolved a variety of technological design issues. The design of the Reference Cell chamber was finalized at this meeting and it was agreed that four identical chambers would be fabricated to determine the feasibility of the Reference Cell concept. These chambers were to be located at SNL, AT&T, NIST, and the Aeropropulsion Laboratory at Wright-Patterson Air Force Base (WAL). It was agreed that workers at these institutions would make plasma voltage and current measurements, for specified Argon gas pressures, and compare the results.

SEMATECH hosted a second meeting on July 24, 1990, in Dallas. At this meeting, users of the Reference Cell discussed problems in making voltage and current measurements. (By this time, more Reference Cells had been constructed than just the original four). An equivalent circuit model that could be used to calculate plasma voltage and current from the measured voltage and current was adopted. Procedures to be followed in making the voltage/current measurements were also established at this meeting.

The Reference Cell *concept* has two parts.

- Discharge Chamber (System)
- Diagnostic Tool Set

The tool set is used to ensure that a plasma created in one location (laboratory) operates similarly to a plasma created in another location.

Comments:

At this point, it should be noted that the Reference Cell is more than just an experimental apparatus. The Reference Cell is actually a concept that includes two parts: (1) a common cell geometry and (2) a minimum diagnostic tool set. It is not sufficient just to have identical discharge chambers. There must also be a set of diagnostic tools that can be used to verify that different Reference Cells operate in a similar manner, i. e. to insure that a plasma created in one Cell has the same characteristics as a plasma created in another Cell. This is particularly true when using processing gases such as carbon tetrafluoride and sulfur hexafluoride which could alter chamber surfaces (leave deposits, etch materials, etc.). SEMATECH was also very interested in the development of these diagnostics for their potential use in etch process control.

RF Reference Cell Specifications

Stainless-steel chamber

Parallel-plate discharge

Base pressure $< 5 \times 10^{-7}$ Torr

4-inch-diameter cooled aluminum electrodes

Showerhead gas inlet

1-inch interelectrode spacing

Two 8-inch, two 6-inch, and four 2.75-inch ports for diagnostic measurements

Provisions for mass spectrometer sampling through electrode

Comments:

The GEC Reference Cell has a stainless steel chamber. Eight ports are provided for diagnostic measurements: two 8-inch ports, two 6-inch ports, and four 2.75-inch ports. The two 8-inch ports provide optical access to the entire discharge region between the parallel-plate electrodes, allowing for laser and other optical diagnostic measurements throughout the entire volume of the plasma. In the standard Reference Cell configuration, the interelectrode spacing is fixed at 1 inch. Optional hardware has been designed for mass-spectrometer sampling through the lower electrode and for a movable electrode configuration which allows continuous adjustment of the interelectrode spacing from 0.5 to 2.5 inches. The upper electrode is a shower-head design, as in commercial plasma-etching equipment. As discussed later, in many ways, the Reference Cell has very similar types of characteristics to commercial etching equipment.

The four-inch-diameter electrodes have provisions for liquid cooling. At the standard interelectrode spacing, the ratio of electrode diameter to spacing is four. This ratio is somewhat important for comparisons with numerical plasma simulations. Due to the complexity of the problem, most plasma models are one-dimensional in the space variable. Comparisons of model results with experimental results will only be valid if the plasma is one-dimensional, in nature, in the discharge chamber. To insure that the plasma is one-dimensional, the ratio of electrode diameter to interelectrode spacing would need to be infinite. When the Cell design was discussed at the 1988 GEC workshop, it was proposed that a ratio of electrode diameter to interelectrode

spacing of four would be sufficient that the plasma would appear relatively one-dimensional at the center of the electrodes. Since there seemed to be a consensus at the GEC that a ratio of four would be sufficient, and due to other design constraints (chamber size, diagnostic access, etc.), the ratio was set at four. Recent data^{2,3} does suggest that one-dimensional plasma models might be appropriate for describing the plasma at the center of the chamber.

A complete description of the Reference Cell appears in the literature¹ and sets of design drawings are available.⁴

²"Electron and Metastable Densities in Parallel-Plate Radio-Frequency Discharges," K. E. Greenberg and G. A. Hebner, submitted for publication in J. Appl. Phys., November, 1992.

³"Comparison of Experiment and Theory for the Helium RF Discharge," M. E. Riley, K. E. Greenberg, G. A. Hebner, and P. J. Drallos, 45th Annual Gaseous Electronics Conference, 27-30 October, 1992, Boston, MA.

⁴Contact Philip J. Hargis, Jr., Department 1128, Sandia National Laboratories, Albuquerque, New Mexico, 87185. Phone: (505) 844-2821, FAX: (505) 844-3211.

Comments:
Picture of a GEC RF Reference Cell.

Comments:

Schematic diagram of the GEC RF Reference Cell. The top electrode contains a shower-head arrangement of 169 holes through which the gas enters the discharge region. The electrodes are electrically isolated from the rest of the chamber by alumina insulators. The ground shields are stainless steel cylinders that surround the alumina insulators. As their name implies, the ground shields are electrically grounded as is the rest of the chamber; their purpose is to help keep the plasma confined to the region between the electrodes. The power leads to the electrodes are solid copper rods.

Comments:

The Reference Cell has a rather complex pump-out manifold. Gas flows out of the main chamber into a lower pump-out chamber through a series of slots in the lower flange. Four slots arranged around the lower pump-out chamber are used to conduct the gas through a manifold to one common pump-out port. This scheme was developed to reduce angular variations in the pumping speed at pressures above 0.1 Torr. John Torczynski (SNL Department 1512) performed calculations of the angular variation of the pumping speed when gas is pumped out through either 1, 2, or 4 ports arranged in a symmetrical pattern around a chamber. (The calculations were not done specifically for the Reference Cell design; they are meant to illustrate the effects of the number of pump ports). Relatively large variations in the pumping speed occur when one port is used, but the variation is reduced to 10% when 4 ports are used. Variations in the gas pumping speed are particularly important when chemically reactive gases are used. In these cases, pumping speed variations lead to variations in the gas residence time and hence to variations in the discharge chemistry. Thus, the manifold minimizes angular variations in the flow characteristics of the chamber, thereby preserving the cylindrical symmetry of the discharge.

Sandia took the lead role in the development of the Reference Cell.

Many Sandians contributed to the Reference Cell effort:

- **Jim Gerardo, 1120**
Organized first workshop at GEC on the Reference Cell
- **Phil Hargis, 1128**
Chairman of Cell design committee
- **John Torczynski, 1512**
Fluid flow calculations
- **Jack Simchock, 2858**
Drafted Cell blueprints
- **Ken Greenberg, 1128 and Paul Miller, 1126**
Developed diagnostic tool set

Comments:

SNL was the driving force behind the inception of the Reference Cell with many Sandians participating in various aspects of the project. If Jim Gerardo had not organized the workshop at the 1988 GEC, the Cell would never have come to fruition. Phil Hargis was the chairman of the Cell design committee and, ultimately, was responsible for working out a myriad of design problems and for guiding Jack Simchok in drafting the Cell blueprints. John Torczynski performed fluid flow calculations leading to the design of the pumping manifold. Paul Miller and Ken Greenberg developed the diagnostic tool set for the Cell.

This large participation, by a variety of people in a number of different fields, emphasizes the wealth of resources at SNL. Using these resources, SNL can lead national research efforts that significantly impact technology. At the present time, more than forty Reference Cells have been installed at various institutions. The Reference Cell chamber is also a standard catalog item from a number of vendors of vacuum equipment.

Standardized diagnostics are as important as standardized hardware

A standardized set of diagnostics is needed to assure that identical plasmas are generated by reactors at different laboratories.

The standardized diagnostics are a **minimal** set of diagnostics
necessary and sufficient metric for plasma
cost effective
"easy" to duplicate

The standardized minimal diagnostics complement and do not replace other diagnostics.

Sandia took lead in developing measurement methodologies and hardware.

1989 GEC - discussion and consensus on diagnostic tool set:
measure rf voltage and current in **argon** discharges

magnitude and phase of first five harmonics and dc bias

1990 GEC - first data reported by AT&T, NIST, SNL, UNM, and WAL

Comments:

The development of a diagnostic tool set was as difficult as the development of a chamber design. The primary question that had to be answered was: What minimum set of measurements needed to insure that a plasma in one Cell is "identical" to a plasma in another Cell? Unfortunately, the answer to this question was not known. (The complete answer still is not known today.)

At a second Reference Cell workshop held at the 1989 GEC in Palo Alto, many suggestions were made for different diagnostics to be implemented. Prior to interruption by an earthquake, workshop attendees advocated using voltage/current, Langmuir probe, spatially-resolved optical emission, and/or microwave (electron density) measurements. They further proposed that the chosen techniques should be easy to implement and interpret, and be cost effective so that research budgets at Universities and elsewhere would not be strained.

At that workshop and through other interactions, it was decided that measurements of voltage and current waveforms (including dc bias) would be easiest to implement by all groups and would yield the least ambiguous results. It was felt that Cells operating with identical voltage and current waveforms in identical gases probably would have quite similar plasma characteristics. The goal was to apply a set of specified peak-to-peak voltages to the discharge (capacitively coupled) and to record the resulting waveforms. The data would consist of the amplitudes and phases of the first five Fourier components (harmonics) of voltage and current,*

along with the values of dc bias. These data sets would be gathered over a specified range of pressures. The Cell was to be driven asymmetrically, with one electrode powered and the other grounded.

*The plasma is nonlinear in nature. Even if a purely sinusoidal source is used to excite the plasma, harmonics of the excitation frequency can be observed in voltage and current waveforms.

Generalized equivalent circuit for the GEC Reference Cell

Comments:

In principle, voltage and current measurements are straightforward. In practice, however, there were several difficulties. One difficulty was the determination of the plasma voltage and current. It is generally felt that more meaningful information is contained in values of voltage and current at the plasma rather than at the location where the probes are connected to the circuit. Because there is substantial inductance and capacitance in the electrical connections to the discharge electrodes of the Reference Cell, the plasma voltage and current can be quite different from the voltage and current at the measurement point. This necessitated the development of equivalent circuit models that could be used to calculate plasma voltage and current from voltage and current measured at some point away from the powered electrode.

The equivalent circuit for the Reference Cell has been discussed at length.⁵ The complete equivalent circuit of the Reference Cell chamber contains a number of inductances and capacitances. There are the inductances and capacitances of the power leads going to the electrodes, capacitances between the electrodes and the rest of the chamber, and inductance associated with the chamber walls. Of course, there is also an interelectrode capacitance which, for our electrode dimensions and the standard separation, is about 3 pF.

⁵"Electrical Characterization of RF Plasma Discharges," Paul Miller and Mattan Kamon, Sandia Report SETEC 90-0009, August, 1990; "Measurement and Analysis of the Equivalent Circuit of the GEC RF Reference Cell," Joseph T. Verdeyen, Sandia Report SAND 92-7284, September, 1992.

Simplified Equivalent Circuit for the Reference Cell

Comments:

For an asymmetrically driven system (one electrode powered and the other grounded), a simplified approximate equivalent circuit can be used to calculate voltage and current at the powered electrode. Because of the possibility of multiple current paths to different parts of the etching chamber, the electrode voltage and current are not identical to "plasma" voltage and current. Recent work⁶ has quantified various current flows internal to the Reference Cell. Nevertheless, for simplicity, we do not explicitly differentiate plasma and electrode voltage and current in this report.

Voltage and current are measured at some position away from the powered electrode. There is inductance, L , between the measurement point and the electrode due primarily to the inductance of the power lead. There is a capacitance, C , from the powered electrode to ground. This lumped capacitance includes the small interelectrode capacitance as well as capacitance between the electrode and the rest of the chamber. If the values of the inductance and capacitance are known, plasma voltage and current can be calculated from the measured values.

In practice, this equivalent circuit model works quite well for describing the Reference Cell. Minor improvements of the model have been investigated, but calculated values of plasma voltage and current have been relatively insensitive to the improvements.

⁶"Dependence on Excitation Symmetry of Electrical Parameters and Radial Currents in a Parallel-Plate RF Discharge," P. Miller, K. Greenberg, G. Hebner, P. Pochan, and J. T. Verdeyen, 45th Annual Gaseous Electronics Conference, 27-30 October, Boston, MA, 1992.

Measured voltage and current are not the same as the *plasma* voltage and current.

L & C Determination

$$Z(\omega) = j\omega L + 1/j\omega C$$

$$\begin{aligned} V(\omega)/I(\omega) &= Z(\omega) = j\omega L + 1/j\omega C \\ V(2\omega)/I(2\omega) &= Z(2\omega) = j2\omega L + 1/j2\omega C \\ V(3\omega)/I(3\omega) &= Z(3\omega) = j3\omega L + 1/j3\omega C \\ &\text{etc.} \end{aligned}$$

Comments:

In order to solve for plasma voltage and current, the parameters of the equivalent circuit must be determined. To obtain values for L and C in the simplified equivalent circuit model, we apply a 13.56-MHz pulse train to the empty Cell (pressure $< 5 \times 10^{-7}$ Torr). Due to the high spectral content of a pulse, this is equivalent to exciting the Cell not only at 13.56 MHz, the fundamental frequency, but also at the harmonic frequencies: 27.12 MHz, 40.68 MHz, etc. For excitation of an empty Cell, the plasma current must be zero so we determine the values of the parameters L and C needed to make the calculated plasma current go to zero at two different frequencies. In the absence of a discharge, the impedance, **Z**, of the L-C circuit is given by:

$$\mathbf{Z} = j\omega L + 1/j\omega C.$$

We measure the voltage and current at the fundamental and harmonic frequencies when the pulse train is applied and use the impedance relationship

$$\mathbf{V/I} = \mathbf{Z}$$

to obtain a set of complex equations that can be used to calculate L and C values. (**V** is the complex voltage and **I** is the complex current in the impedance equation.) If we choose to set the current at the fundamental and second harmonic to zero, we solve these two complex equations simultaneously to obtain values for L and C:

$$\mathbf{V(\omega)/I(\omega)} = j\omega L + 1/j\omega C$$

and

$$\mathbf{V(2\omega)/I(2\omega)} = j2\omega L + 1/j2\omega C,$$

where ω is the angular frequency of the fundamental: $2\pi \times 13.56 \times 10^6$ rad/s. This gives the values for L and C used to calculate plasma voltage and current.

V,I diagnostic system takes snapshot of steady-state plasma

Typical system:

Probes connected "close" to powered electrode, downstream of matching network.

Use electrical equivalent circuit model (series L, shunt C) to calculate V & I at powered electrode.

Use FFTs to perform spectral analysis.

Oscilloscope averages waveforms for several seconds, computer requires several seconds to acquire data and perform calculations.

Comments:

We developed a computer controlled data acquisition system for rapidly measuring voltage and current and calculating plasma values from the measured values. The acquisition system uses a Tektronix 2430A digital oscilloscope to obtain and digitize voltage and current waveforms. Computations are performed using an IBM AT computer (or compatible) that is connected to the oscilloscope using a National Instruments IEEE-488 interface. We wrote approximately 1000 lines of code to acquire the data, properly prepare the waveforms for input to an FFT, perform the FFT, solve the circuit equations, etc. This system allowed for rapid real-time data analysis that speeded study of equivalent circuit analysis and gathering of plasma data. Some of the software and techniques were transferred to AT&T, University of New Mexico (UNM), WAL, and the University of Michigan.

Comments:

Reference Cell data obtained at a number of different laboratories were compared. If things are "done properly" we found that, indeed, plasmas with similar characteristics can be obtained in different Reference Cells for a given set of input conditions. This is shown, for example, by the good correlation of DC Bias vs. Current in Cells at NIST, SNL (multiple cells), UNM, and WAL. In this example, the current is at the fundamental frequency (13.56 MHz).

In order to obtain similar behavior in different Cells, we found that it is not sufficient just to have identical plasma chambers. To obtain similar behavior, also requires identical external circuits for powering the chambers.

V1,I1,I2,I3 Polar Plots
 DC-Bias
 0.50 Torr Argon

Comments:

This transparency shows another example of how good agreement of Reference Cell data can be obtained if the two systems are identical. This is a polar plot showing measured values of plasma voltage at the fundamental frequency (V1), DC Bias, and plasma current at the fundamental frequency and two harmonics (I1, I2, I3); the data are shown for four different voltage levels. The phase of the current at 13.56 MHz, I1, was defined to be zero degrees. The DC bias is plotted at 90 degrees for simplicity - obviously the bias has no phase angle with respect to the other parameters. The data presented are for a Reference Cell at SNL and for another Cell at UNM.

When data from the two Cells were first compared, large discrepancies were observed; for example, the DC biases in the two Cells varied by as much as a factor of two. This was quite puzzling as the two Cells were virtually identical. In fact, the only difference between the two chambers seemed to be that the Cell at UNM was powered by a Branson rf generator and the Cell at SNL was powered by an ENI generator. When SNL's ENI generator was taken to UNM and used to power the Cell there, the plasma characteristics in the UNM Cell changed greatly and became comparable to those in the SNL Cell. This transparency shows the data when the ENI generator was used as the power source for the SNL and UNM Cells. This shows that the external circuit has a strong effect on the plasma.

Plasma voltage and current are affected by the external circuit including all elements back to the rf generator.

Plasma Voltage = 57 ± 4 Volts

Comments:

When the Reference Cell concept was originally discussed at the 1988 GEC, there was a great deal of reluctance by attendees of the workshop to incorporate the external circuit (matching network, rf generator, cables, etc.) into the cell specification. The primary reason for this hesitance was cost; it was thought that if too many parameters were specified, it would "price out" many groups that would otherwise be interested in setting up a Reference Cell system using equipment (rf generators, etc.) they already owned. While there was some concern expressed at the workshop that the external circuit (all elements extending from the electrodes back to the generator) would affect the behavior of the plasma, it was not known how large the effect would be. It was decided, therefore, that these elements would not be specified until some experimental measurements were made to determine the extent of the effects.

The first experiments showing the effect of the external circuit elements were conducted at SNL. The general idea of the simplest experiment performed was to vary the external circuit and to measure plasma current for a constant value of plasma voltage. The external circuit was varied by changing the length of the power input lead, i.e. changing the inductance. The results of this experiment are shown here. This transparency displays the magnitudes of the first two Fourier components of the plasma current as a function of the resonant frequency ($1/2\pi\sqrt{LC}$) of the Cell's equivalent circuit (recall the simplified equivalent circuit transparency). This is a convenient way to

display changes in the external circuit, but it is not unique. Different combinations of L and C values can give the same resonant frequency but might cause different behavior of our non-linear plasma load. For all of the data in the figure, the plasma voltage was calculated to be 57 ± 4 volts. These data clearly show that the plasma is strongly affected by the external circuit. For almost-constant plasma voltage, the discharge current displayed large variations (factor of two) as the external circuit was changed. This strong influence of the external circuit on the plasma characteristics is not completely surprising considering that the plasma is a non-linear element which is generating harmonics and essentially driving the external circuit at the higher frequencies.

The conclusion that must be drawn is that two different Reference Cells (or commercial reactors, for that matter) will not display the same behavior unless everything is identical. Not only must the vacuum chambers be identical, but so must be the power connections, matching networks, cables (type and length), and rf generator output impedance (at all harmonics).

A filter can be used to isolate the external circuit components.

Comments:

Now that we have insisted that everything must be identical for different plasma systems to operate the same way, we discuss a little trick. As an alternative to making all of the external circuitry identical on all of the Reference Cells, Paul Miller developed a low-cost filter that can be used to isolate the chambers.⁷ The concept is to place a low-pass filter between the chamber and all of the other external circuitry (rf generator, matching network, etc.). The filter prevents harmonics generated by the plasma from reaching the other external circuit elements. Then it should only be necessary to have identical filters and circuitry from the filter to the chamber; it should not be necessary to have identical rf generators, matching networks, matching network settings, etc.

SEMATECH is pursuing patent protection for the filter concept.

⁷"Electrical Isolation of Radio-Frequency Discharges," P. A. Miller, H. M. Anderson, and M. P. Splichal, J. Appl. Phys. **71**, 1171(1992).

Data taken at Sandia and UNM show that the filter works.

Comments:

The filter works exceptionally well for isolating the external circuitry. This transparency shows data taken at UNM in collaboration with SNL. The value of the dc bias measured for a constant set of conditions is shown as a function of rf generator, with and without the filter. The left half of the transparency shows the results without the filter. Without the filter, using the first rf generator, Gen-1, the measured bias was about 155 V. When Gen-2 (a different rf generator from a different manufacturer) was used, the bias was less than 130 V. As shown on the right side of the transparency, when the filter was in place, it did not matter which rf generator was used; within the experimental uncertainty, the dc bias was the same in both cases.

Optical and electrical data prove that filter isolation works. Example:

300 Vpp rf in all cases
100 mTorr argon

Comments:

Another example of the effect of the filter is shown with this transparency. This data, taken at UNM, shows the optical emission at 750 nm from an argon plasma. Again, the data were taken with a constant rf voltage. When the Branson rf generator was used, the optical emission was about 7000 arbitrary units. When the Branson generator was replaced with an ENI rf generator, the emission dropped to less than 4000 arbitrary units. With the filter in place, the optical emission was independent of the type of rf generator used.

The fact that the optical emission changes as a function of the external circuit points out the fact that the fundamental plasma properties are strongly influenced by the circuitry. Electron densities and/or the electron energy distribution function in the plasma can be varied by varying the external circuit elements.

Since the external circuit does affect the plasma so strongly, it is possible that the circuit could actually be used as another "knob" for controlling etching processes. The idea of plasma control using the external circuit was transferred to SEMATECH; SEMATECH is pursuing patent protection for the concept.

MDL = opportunity to apply research methodologies to industrial problems

Workers in industry report that nominally identical reactors do not perform identically when using the same recipes. This is a problem with reactors from many different manufacturers.

MDL workers reported that adjacent Quad chambers etched differently when using the same recipe.

Examination and calibration of gas, water, vacuum, and rf systems by standard means didn't cure the problem.

Chamber cleaning and conditioning didn't cure the problem.

Approach:

Electrical diagnostics developed for the GEC RF Reference Cell should be able to identify the source of the problem.

Comments:

The initial work with the GEC Cell was to determine whether a plasma created in one Cell was identical to a plasma in another Cell. Using the knowledge gained from the GEC Cell studies and the diagnostics developed for those studies, we believed we could attack a problem identified by the semiconductor industry: nominally identical reactors do not perform the same way when using the same recipes.

The phenomenon of chamber-to-chamber irreproducibility was also observed and was a problem in the MDL. In particular, chamber-to-chamber variability was observed on different chambers of the Drytek Quad multichamber single-wafer etcher. We decided to conduct an electrical characterization of the Quad reactor to determine the cause of the variability. The particular reactor we studied had two chambers that were used for silicon dioxide etching and two chambers used for polysilicon etching.

Initial work: gather baseline data, adapt hardware & software to Quad

Performed oxide etches on two adjacent chambers with identical recipes:

640 mTorr 100 sccm C₂F₆, 6-mm gap (later 700, 50)

timed etches - 2 minutes (later 1.5)

1-minute O₂ clean between etches

150-mm diam wafers, 630-nm-thick steam oxide, patterned using field oxide reticle

Capacitive and inductive probes (V & I) were added to housing above matching network, below chamber.

Vector impedance meter determined series L and shunt C between V-I-measurement point and powered electrode.

Comments:

We started out by studying the two oxide chambers on the Quad reactor. The first step was to make sure that all of the peripheral gas-handling equipment was identical on the two chambers. The flow controllers and pressure gauges were calibrated. In addition, the chambers were both cleaned in an identical manner to remove any possible effects due to previous utilization.

Next, a set of wafers was etched in each chamber to serve as a baseline of how much variability existed between the two chambers. We also developed an adapter containing simple "home-made" capacitive and inductive pickups for sampling the voltage and current. The adapter replaced an existing metal cover on the reactor that surrounded the bottom of the power lead to the electrode. Installation of the adapter takes just a couple of minutes.

Initial status: Chambers #1 and #2 perform differently when using identical recipes

Comments:

For the initial set of baseline data, dc bias and oxide etch rate were measured as a function of generator power. The Drytek Quad is operated completely under computer control. The operator specifies a power at the rf generator and the computer maintains that power during the time of the etch.

This transparency displays the results of the baseline measurements. Both the dc bias and the etch rate varied significantly from chamber to chamber. For example, at 700 W, the dc bias in chamber 1 was approximately 3 times the bias in chamber 2 and the etch rate in chamber 2 was 25% higher than that in chamber 1.

Based on our experiences with the Reference Cell, we knew that all electrical parameters of the rf circuits had to be identical if we expected to get similar plasma characteristics. Therefore, we decided to investigate the electrical characteristics of the two oxide chambers themselves and the electrical characteristics of the external circuit of each chamber.

Simple L,C equivalent circuit allows computation of plasma V & I

Comments:

The characteristics of the two oxide chambers were examined first. This transparency shows a schematic diagram of a chamber on the Quad reactor. While the Quad reactor is not physically the same as the GEC Reference Cell, it turns out that electrically, chambers on the two systems are quite similar. An equivalent circuit diagram for a chamber on the Quad reactor is identical to the simplified L-C equivalent circuit for the Reference Cell. Just as for the Reference Cell, the chambers on the Quad reactor are characterized by an inductance associated with the power lead to the electrode and by a capacitance between the powered electrode and the rest of the chamber.

L,C model fits reactance data to 60 MHz; chambers are quite similar

Comments:

In order to determine the electrical characteristics of the two oxide chambers, we used a vector impedance meter to measure the complex impedance of each chamber as a function of frequency from 0.5 to 100 MHz. The two chambers appeared to be virtually identical between 0.5 and 40 MHz with only minor differences all the way out to 100 MHz. A nonlinear least-squares fit to the data showed that a simple L-C equivalent circuit model fits the reactance data quite well to 60MHz.

Since the two chambers were so much alike, it did not appear that differences in the electrical characteristics of the chambers themselves were the cause of the chamber-to-chamber variability. Therefore, we shifted our attention to the external circuitry and, in particular, to the matching networks.

Matching-network impedance showed resonance due to stray capacity

basic network design:

important stray capacitances:

Comments:

Matching networks are used in rf circuits to match the impedance of the rf generator to the impedance of the load, thus improving power transfer. Each chamber on the Quad reactor has a separate matching network and rf generator. A schematic diagram of the actual Quad matching network circuitry is shown on the transparency and labeled "basic network design." The network consists of a variable shunt capacitor and an inductor in series with a second variable capacitor. The reactance of such a circuit, measured at the output terminal, should be negative at low frequency, increase through zero, and then continue to increase monotonically as the frequency increases. It would look similar to the following:

When we used the vector impedance meter to measure the reactance, however, we obtained the characteristic on the right side of the transparency. As shown, a pole is present in the reactance data near 35 MHz. This pole indicates that stray

capacitance strongly affects the impedance of the matching networks. It should also be noted that the pole is near the third harmonic of the excitation frequency. If the position of the pole (in frequency) is just slightly different between matching networks, the impedances at the second and third harmonics can differ significantly. If the impedances at the harmonics are different, then it means that the external circuits are different.

Stray capacitance in the matching networks could cause a great deal of variability. When we looked inside several matching networks, the inductors all appeared to be different to varying degrees. The inductors were not wound on forms and had slightly different separations between turns.

Chamber-#1 data show that network impedance variations affect etch rate and dc bias

feature	Network #1		Network #2	
	frequency	impedance	frequency	impedance
zero	11.6 MHz	1 Ω	11.5 MHz	2 Ω
2nd harmonic	27.12	320	27.12	250
pole	34.1	16500	36.75	25000
3rd harmonic	40.68	500	40.68	860
4th harmonic	54.24	158	54.24	180
				0°
				+70°
				0°
				-88°
				-90°

Comments:

Since there seemed to be so much variability in the matching networks, we investigated chamber performance differences due to the networks. In this case, all etching was done in chamber #1, but two different matching networks were used. A set of wafers was etched with network #1. Network #1 was then replaced with network #2 and another set of wafers was etched. As shown in this transparency, switching the networks had a profound influence on the etch rate and dc bias in the chamber.

At the bottom of the transparency are shown the impedances of the two networks as a function of frequency. The position of the pole differs by only 2 MHz for the two networks, but the impedances at the second and third harmonics are quite different.

Several changes were required to equalize rf-system impedances

1. The shaft positions of C1 and C2 were equalized in different networks with respect to the shaft-position-encoder output. That is, after the adjustments, equal C1 display indications on the control monitor for two different chambers mean equal C1 capacitances.
2. The inductors were adjusted (bent 2 to 3 mm by hand, trial-and-error) to equalize the frequencies of the impedance pole near 35 MHz.
3. The values of C1 and C2 at the start of the discharge were made the same for different chambers.

Initial values of C1 and C2 should be made a part of the process recipe. Because of plasma nonlinearity, there is no guarantee that different starting positions will lead to the same plasma history.

4. The lengths of coaxial cable between the mainframe bulkhead and the matching networks were made equal.

Comments:

Since the external circuits, particularly the matching networks, were different for the two oxide chambers, we attempted to minimize all external circuit differences. The major change was the adjustment of the matching networks. We chose three matching networks and tried to make them as identical electrically as possible. The adjustments are listed on the transparency. After adjusting the matching networks, we chose the two that appeared most alike for more the next studies.

Comments:

After adjusting the three matching networks A, B, and C, the reactance of each network was measured as a function of frequency. Networks B and C were found to be most similar and were chosen for the next studies.

Final status: Chambers #1 and #2 perform similarly

Comments:

Etch rate and dc bias were measured again. The measurements were made in the two oxide chambers using the matching networks that had been adjusted. Now, very similar characteristics were observed for the two chambers.

The solid lines on these plots are fits to the data and the dotted lines are 99% confidence limits for the fits. When the data are plotted as a function of power at the generator (the control knob set by the operator), the confidence limits are tight but there is a little bit of spread in the data.

Final status: Performance is more closely correlated to current than to power

Rate & bias vs. current (rather than vs. power):

The two chambers are better matched and there is less spread in the data for each chamber.

Current is a plasma parameter, whereas power is a generator parameter.

Comments:

This transparency shows the same etch rate and bias data as the previous transparency, except now the data are plotted as a function of measured current to the chamber. Again, the solid lines are fits to the data and the dotted lines are 99% confidence limits. There is much less spread in the data when plotted vs. current than vs. generator power. This suggests that current would be a better parameter than power for controlling the etching process.

Remaining differences could be due to a 2% current-calibration error

Comments:

This transparency shows the same data as the last one except the data are overlaid on one plot. It is easy to see how close in performance the two chambers are after the adjustments to the external circuits. The remaining differences between the two chambers can be attributed to calibration errors of the current probes. As stated earlier, we used home-made inductive pickups to sample the current to the chamber. Calibration of these probes was difficult due to the physical layout of the Quad reactor. A 2% calibration error could explain the remaining discrepancies.

Chamber-to-chamber reproducibility and wafer-to-wafer variability were improved greatly

Comments:

This is a summary of the data before and after adjusting the external circuits. The "After" plots show the data as a function of generator power and as a function of current to the chamber.

Data: Over many tests, 99% confidence limits on etch rates at fixed "power" were typically ± 150 A/min, whereas etch rates for fixed "current" were ± 50 A/min, where:

"power" means generator power averaged over the entire etch cycle,

"current" means measured current averaged over only 15 s in the middle of the etch.

Therefore, current control should decrease etch-rate variability by 3X or more.

Comments:

When current was measured during an etch, it was only averaged over 15 seconds during the middle of the etch. The generator powers were averages over the entire etch. Therefore, the data indicate that, at a minimum, current control should decrease etch rate variability by a factor of three.

Initial poly data show significant chamber differences

Comments:

Initial baseline measurements have been made on the two polysilicon etching chambers on the Quad reactor. These baseline measurements also show chamber-to-chamber variability. We are confident that the same procedures applied to the oxide chambers will improve performance in these polysilicon chambers.

Plasmas are rich in phenomenology (ref. T.I., Tegal, U.T.)

Comments:

We now change topics slightly to the field of chaos as it relates to plasma reactors. Colleagues from Texas Instruments had suggested that we look for the generation of electrical signals at frequencies below the drive frequency. In work at TI and the University of Texas, they had seen such subharmonic signals, but the signals had neither been understood nor reported in print.

Later we talked to an engineer at Tegal whose customer had problems with subharmonics in reactors delivered by Tegal. The customer operated the reactors at higher power than they were designed for. The customer observed subharmonics that coincided with bad process results. The customer told Tegal to eliminate the subharmonics or else! The engineer found a cure using trial-and-error changes to the electrical drive circuitry.

In some experiments we also encountered low-level subharmonics generated by the Drytek reactor chambers.

Erratic performance occurred near threshold of period-doubling bifurcation

"Period doubling" - another important nonlinear phenomenon

alternation between two states on successive rf cycles
causes subharmonic generation ($f/2$, $3f/2$, $5f/2$, ...)
mathematical property of all nonlinear dynamical systems with
 ≥ 2 degrees of freedom
generally a precursor to chaos

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V & I signals showed presence of subharmonics

present at start of discharge at moderate and high powers
more likely to persist throughout discharge at higher powers
presence affected by pressure, flow, and impedances

Appl. Phys. Lett. 60, 2859 (1992).

Comments:

We found that subharmonic generation is a well-documented phenomenon in many periodically-driven nonlinear systems. Generally, as excitation is increased, a threshold is encountered above which subharmonics are generated. The first subharmonics to occur are usually at $1/2$ the excitation frequency. Consequently, the phenomenon is known as a period-doubling bifurcation.

As excitation is increased further in many nonlinear systems, more subharmonics occur (e.g. at $1/4$, $1/8$, $1/16$... of the drive frequency) until a level is reached above which the system becomes chaotic (totally unpredictable).

We published our findings for the plasma reactor.⁸

⁸"Period-Doubling Bifurcation in a Plasma Reactor,"
P. A. Miller and K. E. Greenberg, Appl. Phys. Lett.
60, 2859(1992).

Basics of period doubling

"Chaos" denotes erratic, unpredictable behavior and hypersensitivity to initial conditions.

Period doubling (alternation between two states) is frequently a precursor to chaotic behavior. It causes subharmonic generation.

Mathematical descriptions:

differential equations $\longleftrightarrow$ dynamical systems (plasmas, planets)
difference equations $\longleftrightarrow$ periodic snapshots of dynamical systems

Poincaré return map: intersection of trajectory through phase space of dimension N and surface of dimension $N-1$.
Orbit "O" is periodic,
orbit $x + /x-$ is period doubled.

Comments:

Period-doubling bifurcations and chaos are seen in many dynamical systems described by differential equations as well as simple iterated equations such as the logistics equation

$$X_{n+1} = A - X_n^2$$

which has been treated in much popular literature.

Magnitude of subharmonics was small, but change in etching was large

Lesson: adjust recipe and/or electrical circuits to avoid operating near the threshold of such a bifurcation.

Comments:

In one experiment, signals at $1/2$ the drive frequency were found in the rf voltage and current signals from the Drytek reactor as power was increased above 700 watts. Signals at multiples of that frequency (i.e. $3/2$, $5/2$) were also present. The amplitudes of those subharmonics were small, in the 5% range, but they were correlated with significant changes in etch-rate trends and dc bias.

The graphs on the left show the signal magnitudes. The graphs on the right show the etch rates and dc bias. The open circles in the dc-bias graph show the standard deviation of the bias during the two-minute wafer etch-period at each power. High deviation means that the bias changed significantly during etching. The open circles in the etch-rate graph denote the normalized variation in the etch rate at 110 sites measured across the surface of each wafer. (The process had not been optimized for uniformity.)

Note that as power is changed from 650 to 750 watts, the etch rate drops slightly while the dc bias doubles. Operation with this process at 700 watts would be erratic. By trial and error, we were able to modify the process and thereby shift the subharmonic generation and associated erratic behavior to higher powers. We subsequently operated the reactor in a stable mode near 700 watts.

Spectrum analyzer output:

ref. P. S. Lindsay, Phys. Rev. Lett. 47, 1349 (1981).

Comments:

Several groups have studied RLC circuits that use a varactor diode as a voltage-dependent capacitor. They report subharmonic generation in such circuits and have modeled those circuits with apparent success. However, there have been disagreements concerning whether voltage nonlinearity or charge-storage time is the dominant factor in the period-doubling behavior. Others report very complex behavior of such simple circuits when driven at different frequencies. This is still a research area.

We currently are examining this problem as it applies to plasma reactors.

Summary

Nonlinear electrical phenomena are widely ignored but important in controlling plasma behavior.

Reproducibility among chambers can be achieved:

Match rf components over wide frequency range,

- or -

Use filter between matching network and chamber.

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Wafer-to-wafer variability can be reduced:

Replace power control by current control.

These process improvements can lead to:

Faster turn-around and better devices at Sandia,

Higher yield in industry.

Our 1100/1300 collaboration is technically successful and enjoyable.

Comments:
See the summary (Section IV) of this report.

Future work

1. Extend work with Quad's oxide chambers to poly chambers.
2. Implement current control on Quad.
3. Adjust new matching networks for oxide chambers.
4. Investigate period-doubling phenomenon with
analytic modeling,
GEC Reference Cell,
Quad.
- * * 5. Investigate improved end-point detection using
electrical diagnostics,
optical diagnostics,
microwave diagnostics.