Control of the RF Waveform at the Chuck of an Industrial Oxide-Etch Reactor

Lee Berry¹, Helen Maynard², Paul Miller³,⁴, Tony Moore¹,⁴, Michael Pendley⁴, Victoria Resta⁴, Dennis Sparks¹, and Qingyun Yang⁴,⁵

¹ Oak Ridge National Laboratory, Box 2009, Oak Ridge, TN 37831.
² Bell Laboratories, Lucent Technologies, 700 Mountain Ave., Murray Hill, NJ 07974.
³ Sandia National Laboratories, Box 5800, Albuquerque, NM 87185-1423.
⁴ SEMATECH, 2706 Montopolis Dr., Austin, TX 78741.

Abstract

Radio frequency (rf) power is applied to the chuck of a high-density plasma reactor in order to extract ions and to control the energy of the ions used for the fabrication of microelectronic devices. In many cases, the temporal shape of the rf waveform largely determines the shape of the spectrum of those extracted ions, thereby strongly affecting feature evolution. Using auxiliary rf circuits we successfully made major changes to the rf potential waveform at the chuck of an Applied Materials 5300 HDP Omega reactor without affecting the normal functioning of the reactor's control systems. This work established the practical feasibility of techniques for modifying the ion energy distribution functions of industrial reactors.

¹ electronic mail: pamille@sandia.gov
² present address: IBM.
I. INTRODUCTION

Radio-frequency (rf) bias power is used to extract ions from the bulk plasma in high-density plasma reactors in order to modify materials in the fabrication of microelectronic devices and in other applications. The extraction of the ions is controlled by the potential difference between the workpiece and the bulk plasma (which is at the plasma potential $V_p$). That potential difference is developed across a thin plasma sheath that develops near the surface of the workpiece. The energy, species, and flux of the extracted ions affect the interaction of the ions with the workpiece. If the transit time of the ions across the sheath is comparable to or shorter than the period of the rf bias power, then the shape of the ion energy distribution function is controlled by shape of the rf-potential waveform. To a fair degree of approximation, the total applied bias power controls the peak and total energy of the extracted ions, while, in contrast, the shape of the potential waveform controls the shape of the ion distribution function.

For some processes, like anisotropic oxide etching, a difficult-to-achieve balance is needed between competing chemistries. For such processes it is generally believed that subtleties, such as the shape of the ion distribution function, not just the total ion energy, are important for achieving optimal performance. Electrically, the plasma sheath is a nonlinear circuit element that gives rise to harmonic generation at the chuck. The presence of rf-potential harmonics means that the chuck potential waveform is not a simple sinusoid. Control of the harmonics is identical to control of the shape of the chuck waveform, and, consequently, to control of the ion energy spectrum.
DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, make any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.
DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.
Previous work\textsuperscript{3} with a laboratory research reactor using non-reactive gases demonstrated successful first-principles modeling of sheath dynamics, including the harmonic generation process and the relationship between harmonics and plasma properties. Moreover, it was suggested that modification of rf circuits at the chuck could change the chuck potential waveform, thereby modifying the shape of the ion energy spectrum. More recently, direct control of the waveform at the chuck of a research reactor has been reported\textsuperscript{4}. In the present work, two types of auxiliary circuits were developed for controlling chuck harmonics in a high-power industrial reactor in order to test the concept of harmonic control on a larger scale and to identify practical difficulties in implementation.

The reactor selected for this project was an Applied Materials 5300 HDP Omega reactor that was an inductively coupled reactor used for oxide etching located at SEMATECH in Austin, TX. Another Omega reactor located at Bell Laboratories, Murray Hill, NJ, was used for preliminary measurements and for circuit analysis. This particular brand of reactor was selected because of its availability and other practical considerations, and it was not selected for any unique design or performance features. Waveform control was successfully achieved by modifying the rf circuitry of the chuck in ways that did not affect the normal functioning of the reactor controls nor of the standard rf generator and matching network. As part of this work, a limited amount of wafer etching was performed using both a standard SEMATECH recipe and modified recipes. The etch analyses showed that, while the modified chuck potential waveform did affect processing, no obvious beneficial effects resulted. Section II of this paper describes the general concepts of waveform control and Sec. III describes specific circuits used for
waveform control. Section IV presents our results and Sec. V describes a first-principles attempt to model the rf circuits and plasma sheath.

II. WAVEFORM-CONTROL CONCEPTS

For our purposes, the important parts of the chuck’s rf circuitry are the rf generator, matching network, rf transmission cables, the chuck itself, and the plasma sheath. Harmonics are generated in this circuitry solely because of the electrical nonlinearity of the plasma sheath, not because of any of the rest of the components. However, the harmonic amplitudes and phases do depend on the characteristics of the chuck-circuit components. The ratios of the chuck potentials and currents at each harmonic frequency, as measured at the chuck, must equal the impedance of the rf circuitry connected to the chuck at each harmonic frequency. As a simple example, if the impedance of the circuitry connected to the chuck has zero impedance at a particular harmonic frequency, then the chuck potential waveform cannot have any component at that frequency. Also note that if the impedance of the circuitry is purely reactive at a particular harmonic frequency, then the potential and current must have \( \pm 90^\circ \) relative phase at that frequency. Consequently, there cannot be any net power flow at that harmonic even though the harmonic potential and current magnitudes may be large at that frequency.

The foregoing conceptual analysis leads directly to one technique for controlling the chuck’s potential waveform that we term “passive” control. That technique is to control the impedance of the circuits connected to the chuck at one or more selected harmonic frequencies. This control can be achieved by connecting a passive auxiliary circuit in
parallel with the chuck that (1) has high impedance at the fundamental excitation
frequency and (2) has adjustable impedance at selected harmonic frequencies. This
arrangement will result, for example, if a series section of the auxiliary circuit is a
parallel-resonant L-C circuit tuned to the fundamental frequency. Feature 1 is desired
(but not absolutely necessary) so that the load presented to the rf generator and matching
network at the fundamental frequency is not directly affected by the passive auxiliary
circuit. Feature 2 implements control of harmonic impedance(s), and, thereby, control of
chuck potential waveform. As the adjustable impedance is varied, the harmonic content
of the chuck waveform will be affected.

An alternative way to control the chuck potential waveform is to connect to the
chuck an active rf power source that injects a desired signal at a one or more selected
harmonic frequencies. This approach is termed “active” harmonic control. As with
passive control, the connection of the auxiliary power source to the chuck should have
high impedance at the fundamental frequency so that it does not directly affect the load
presented to the tool’s own rf generator and matching network. In order for the auxiliary
power supply to provide a temporally synchronized modification to the chuck waveform,
its signal must be phase locked to the fundamental excitation frequency.

The passive control technique is advantageous over the active technique precisely
because it employs passive components that are comparatively simple. However, the
range of harmonic control available in the passive technique is limited by the plasma
sheath properties in a manner that is not easy to predict. This could be a severe
limitation. In contrast, in principle, the active technique promises essentially unlimited
control over the harmonics since the magnitude and phase are dictated by the auxiliary
power source. However, as discussed below, practical difficulties can limit the flexibility of the active technique.

Both active and passive techniques, as described above, use a series circuit with high impedance at the fundamental frequency to decouple the auxiliary circuits from the tool's circuits at the fundamental frequency. This may reduce, but it will not eliminate, the effect of the harmonic control on the tool's rf generator and matching network. If harmonic control is implemented and if it modifies the plasma sheath behavior, then that modification can affect the impedance of the plasma as seen by the chuck circuits at the fundamental frequency. Because the system is nonlinear, such interactions are difficult to predict with confidence, wherefrom arises the need for experimental tests.

III. WAVEFORM-CONTROL IMPLEMENTATION

A system was designed that allowed for testing of both the active and passive modes of harmonic control in a single experiment. The components used for passive control also were used as part of the active-control circuit. The fundamental excitation frequency of the chuck was 1.8 MHz, and we elected to design circuitry that controlled the second harmonic at 3.6 MHz. We also decided to design circuitry that had minimal influence on the third harmonic at 5.4 MHz. Figure 1 shows the circuit layout. The top row of components in Fig. 1 represents normal parts of the reactor. The auxiliary components were connected to the standard reactor circuits at two points. A high-impedance capacitive pickoff (at the left) provided a source signal that ensured that the actively-generated harmonic signals were phase locked to the fundamental excitation frequency.
A set of tuned L-C circuits (at the right) connected to the chuck. In this reactor, a length of coaxial cable transmitted rf power from the matching network to the chuck. Consequently, the connection from our auxiliary circuits to the chuck was made simply by using an HN coaxial tee inserted into the transmission circuit.

The tuned circuits in Fig. 1 are grouped in two boxes. The top box contained two tuned circuits that were designed to resonate at the fundamental frequency F and at the third harmonic 3F, thereby preventing signal flow at those frequencies from the chuck into the auxiliary circuits. The top box also contained a resistive voltage divider to measure chuck potential and a dc blocking capacitor, which are not shown in Fig. 1. In the passive mode of operation, the switch in Fig. 1 was left in the open position as shown. The tuned circuit in the bottom box could be adjusted to resonate above and below the second-harmonic frequency 2F. As that circuit was tuned, the impedance presented to the chuck at the second harmonic varied over a wide range of both capacitive and inductive impedances, while the impedances at the fundamental and third harmonic remained very high. The actual experimental situation was somewhat more complicated than this due to stray capacitance to ground associated with the tuned circuits and with the connection to the chuck. Those strays caused interactions in tuning of the individual circuits. Consequently, in order to adjust the passive system, we used an iterative tuning procedure while the impedance poles of the complete circuit were measured with a network analyzer.

In the active mode of operation, the switch shown in Fig. 1 was closed. A small 1.8 MHz signal (< 5 Vpp) was fed into the passive frequency doubler. The doubler used a full-wave diode rectifier and several tuned circuits that provided high isolation of input
and output at all frequencies. The isolation was needed to prevent self-oscillation of the closed loop that is present in Fig. 1 when the switch is closed. (We never encountered any problems in this regard in our work.) Phase control was obtained in the doubler by varying the tuning of one circuit that was resonant at 3.6 MHz and by switching the polarity of the diodes. The 3.6 MHz signal was fed into an rf amplifier and a matching network, and then into the set of tuned circuits connected to the chuck.

IV. RESULTS

The nominal operating conditions of the reactor for this experiment are listed in Table 1. All process steps were run with a fully open throttle, leading to a pressure of approximately 6 mTorr for the main etch step. Neither the in situ photoresist strip step nor the preceding transition step was used for most of the wafers in this study, as we were interested in studying the thickness and profile of the remaining photoresist. For those wafers that did not see a photoresist strip step, the strip was run on a subsequent dummy wafer (blank Si) to prevent polymer buildup on the chamber walls. Conditioning wafers were also run for each new process condition. In addition, "warm-up" wafers were run at the beginning of every lot to ensure a stable operating temperature for the Si roof, which controls much of the plasma chemistry. The silicon chamber roof was held at 270° C, the wall temperature was 220° C, and the chiller temperature was 10° C. Helium backside pressure was 15 Torr. The harmonic modifications and analysis addressed only the main etch.
Most of the experimental time was consumed trying different adjustments of the auxiliary circuits. During that time, blank photoresist-coated wafers were used in the reactor. Under a few selected conditions we etched patterned wafers coated with 925 nm of oxide (undoped PECVD TEOS), 70 nm of organic anti-reflection coating (ARC), and 800 nm of I-line photoresist.

A. Normal operation

Normal excitation of the chuck of the Centura reactor was at 1.8 MHz and the measured potential waveform ($V_c$) was distinctly nonsinusoidal as shown in Fig. 2. The potential waveform measured on the tool located at Bell Laboratories was essentially identical to that of the SEMATECH tool.

The true ac potential waveform at the wafer differed from the measured potential because of the inductive drop between the measurement point and the wafer. However, as elaborated in Sec. V, the relevant inductance was only 100 nH and the resulting potential drop was small: for 10 A at 1.8 MHz it would be 11 V. Consequently, in our discussions, we treat the measured ac potential waveform as being identical to the chuck’s ac potential waveform. The chuck potential measurements contained an unknown dc offset from the wafer potential because the tool employed an electrostatic chuck. Furthermore, our measurements were made through a dc blocking capacitor. Consequently, we estimated the dc offset, and in what follows we shall not distinguish between the wafer and chuck potentials. The dashed line in Fig. 2 is an estimate of the position of the plasma potential $V_p$, which has been drawn as constant at +20 V with respect to chamber ground.
The silicon disk constituting the roof of the reactor chamber was electrically grounded. The presence of this grounded surface should have prevented large oscillations in $V_p$. In Fig. 2, the dc offset of the chuck waveform has been set to make the most positive chuck potential equal to 0 V. These specific values are not critical to the data interpretation. The main point is that, in the presence of high-density plasma and relatively low chuck excitation frequency, the instantaneous energy of ions impacting the wafer is given by the instantaneous difference $e(V_p-V_c)$. Using this relationship, we can compute a spectrum from the potential data in Fig. 2, as is shown in Fig. 3. As a first approximation and in the absence of direct measurements, we assume that the ion current leaving the plasma is constant in time. With that assumption, the potential spectrum of Fig. 3 is equivalent to the ion energy distribution function. The main implication of Fig. 3 is that the energy of most of the ions impacting the wafer was less than 100 eV in spite of the fact that the peak chuck potential exceeded 600 V. We expect that this conclusion is not particularly sensitive to the assumptions stated above.

B. Passive control

When the three tuned circuits in Fig. 1 were adjusted to present high impedances to the chuck at the three lowest harmonics (1.8, 3.6, and 5.4 MHz), the auxiliary circuitry had no effect on the reactor operation or on the chuck potential waveform. Passive control of the chuck waveform was accomplished by adjusting the tuned circuits away from that high-impedance condition. As the tuned circuits were adjusted, the chuck waveform changed, but it did not do so smoothly and continuously. The nonlinear nature of the plasma was quite evident. During the course of the experiment, we tested various
combinations of adjustments of all three tuned circuits. The adjustments were made while test wafers were being etched. Given the time constraints of that type of operation, we were not able to sample systematically a large fraction of the three-dimensional tuning space that was available to us. A variety of different “distortions” of the basic chuck waveform were achieved. Figure 4 shows an example of a chuck potential waveform that (subjectively) had the largest change from the standard waveform in Fig. 2. It is evident that the modified waveform was very different from the standard waveform. The waveforms were taken using the averaging feature of the digitizer and we found no reason to doubt the reality of the high-frequency “wiggles” on the waveform in Fig. 4.

Figure 5 shows the potential spectra computed from the waveform in Fig. 4. Within the approximations mentioned above in interpreting such spectra, we conclude that the average ion energies were shifted to much higher values, with 50% of the ions having energies above 400 eV.

C. Active control

Active control of the chuck waveform was achieved by closing the switch in Fig. 1 and by applying power to the rf amplifier (rated at 1000 W cw). Conceptually, all that was required to change the chuck waveform was to adjust the amplitude and phase of the applied rf power signal. However, in practice it was rather difficult to realize active control for two reasons: First, the plasma itself was a strong source of second-harmonic power that flowed back into the rf amplifier. Under many conditions, the protection circuits in the amplifier would activate and shut down the amplifier. Second, after the protection circuits were bypassed, it was difficult to understand the complex interactions
of the amplifier, its matching network, and the plasma. For example, in some extreme cases when active control was apparently forcing a change in the chuck waveform, there actually was net second-harmonic power flowing from the plasma back into the amplifier. That is, in those cases, the amplifier was experiencing more reflected power than forward power. That situation seems like an example of passive control.

In light of this, it may be useful to envision active and passive control both as cases in which impedances are connected in parallel with the chuck. For passive control, the real part of the shunt impedance must be positive, whereas in active control the real part can be either positive or negative (or zero, i.e. lossless). Active control also probably allows one to use a larger range of reactances than is possible with practical components in passive tuned circuits.

Under active control, a variety of chuck potential waveforms were achieved. However, none were dramatically different from those achieved under passive control. Figure 4 is, in fact, quite similar to waveforms achieved at one point under active control. While active control still promises greater range of control than passive control, we did not realize that greater range of control in this experiment, perhaps because we did not have enough time to thoroughly investigate the entire control space that was available to us. We did observe that, as with passive control, active control also enabled us to shift the (inferred) ion energy distribution to higher energies.

It is important to note that at no time under either active or passive control did the reactor control systems experience any problems with normal operation, and the tool operator saw no indication of deviations from normal operation.
D. Etching

We etched a limited number of patterned wafers to assess the effects of the waveform modifications on a standard etch process. The patterns contained contact holes ranging from 250 - 500 nm (nominal). The general procedure was to compare pairs of wafers etched with and without modification of the harmonics, under the same conditions of pressure, power, and flow. SEM micrographs provided the bulk of the data for sample analysis.

Oehrlein et al determined that low-energy ions contribute to the polymerization reactions that form fluorocarbon films on the horizontal surfaces and that high-energy ions (i.e. ions above a threshold energy of approximately 50 eV) participate in the etching of the oxide. We therefore expected that by modifying the bias waveform, and therefore modifying the ratio of low- to high-energy ions, that we would change the relative rates of fluoropolymer deposition and oxide etching.

1. Baseline Recipe

We first compared two wafers etched with the same baseline recipe listed in Table 1. The first wafer was etched with the standard chuck waveform, and the second was etched with the auxiliary circuits tuned for a greatly modified chuck waveform, such as in Fig. 4. SEM micrographs of the two wafers are shown in Fig. 6. The wafer etched with the modified circuit had substantially more polymer deposited on it than did the wafer with the conventional circuit. However, we noted that even the completely standard wafer had some features that did not open (e.g. Fig. 6C). We realized that the anti-reflective layer was unusually thick for this lot, and for all subsequent wafers, we doubled the ARC etch time to 60 seconds. Despite the fact that there were issues with the ARC etch, this wafer
pair shows that there is something very different in the etching behavior of the etcher when the chuck waveform was modified, and this difference will be discussed after the next section.

2. Modified recipes

We chose four modifications to the baseline recipe: increase the C\textsubscript{2}F\textsubscript{6} concentration by 15, 30 and 60% over the standard recipe and to decrease the total flow by 30%. These conditions are listed in Table 2. For the first three cases, we kept the total flow constant, to keep both the residence time and the pressure constant. For each recipe, we etched a pair of wafers: one with the standard chuck waveform and one with the auxiliary circuit adjusted to produce a bias waveform similar to that depicted in Fig. 4. The intent was to find the process condition for which the circuit modification had the greatest effect. As suggested by Fig. 5, the ion energy distribution produced by the circuit modification is expected to have the low-energy population decreased relative to the high-energy population. Therefore we expected to see less polymerization and more oxide etching on the wafers with the modified circuit.

Figure 7 compares micrographs for the two wafers etched for condition C of Table 2. Since this recipe had the highest increase in C\textsubscript{2}F\textsubscript{6} concentration, we would expect more polymer to be deposited for both cases, and indeed this was the case. However, unexpectedly, there was more polymer deposited on the wafer etched with the modified chuck waveform. This recipe results in "inverse RIE-lag" which is attributed to the geometric reduction of neutral fluoropolymer reaching the bottom of small contact holes. The limited fluoropolymer flux results in a thinner layer that is easier to etch through; therefore, smaller diameter holes etch more quickly. If, as expected, the chuck-waveform
modification had shifted the ion energy distribution to the higher end of the energy spectrum, then the inverse RIE-lag should have been reduced when etched with the modified circuit.

The observed etch behavior is not understood. One possible explanation for the anomalous result is that the circuit modification might have reduced the overall power to the chuck. Unfortunately, time did not permit making simultaneous measurements of chuck potential and current, and therefore the total chuck power was not computed. Ideally, these etching experiments would be repeated when the total bias power could be held constant. However, we note that the reactor’s control system indicated a constant power level out of the rf generator and, thus, the total available bias power did appear to be constant. Another possible explanation is that the plasma potential was not approximately constant in time, as has been assumed in our analysis, but was strongly modulated by the chuck potential. This would result in an ion energy distribution function much different from those inferred from Figs. 3 and 5. A direct measurement of plasma potential oscillations could be performed simply using a capacitive probe immersed in the plasma. A direct measurement of the ion distribution would be more complex, but it would clarify the situation unambiguously.

The wafer analyses showed no dramatic change in etching due to the change in harmonic content of the chuck waveform. In both the standard case and the case with modified harmonics we noted an inverse RIE lag. The only consistent change was that the modified harmonics, supposedly corresponding to more high-energy ions, consistently enhanced the deposition of polymers. This result was somewhat surprising. However, it is difficult to reach any general conclusions regarding this behavior and the
potential utility of the modified ion energy distribution because the etching system is complex and we did not have the opportunity to optimize a recipe for any cases with harmonic modifications.

V. RF ANALYSIS

Conceptually, the harmonic modification procedure is straightforward and our experimental results demonstrate that harmonic modification can be achieved in practice with an industrial reactor. However, it is difficult to take advantage of this control possibility because there are several degrees of freedom in the harmonic spectra and because the influence of a modified ion energy distribution function on a process is generally not known quantitatively. Consequently, it would be valuable to have first-principles predictive capabilities regarding both the harmonic-generation process and the etching process. Toward that end, we attempted to develop a model of the harmonic-generation process. We were successful in modeling the standard reactor configuration but we were not successful in predicting the observed interaction of the reactor with our auxiliary harmonic-modification apparatus.

To model the rf circuit interaction with the plasma, we employed the modeling procedures reported previously. That is, we used Riley's unified plasma sheath model to describe the nonlinear electrical behavior of the plasma sheath and we coupled that to a detailed equivalent-circuit model of the rf circuits connected to the chuck. A simplified circuit model for the chuck circuits is shown in Fig. 8. The development of the circuit model was based in part on detailed physical examination of the impedance matching
network and cables on the reactor at Bell Laboratories. The model also was based on impedance measurements made with a network analyzer on the reactor at SEMATECH. Specific component values for the equivalent circuit were initially estimated and then adjusted to make the measured frequency-dependent impedance match the values computed with the model. The measurements were made with the network analyzer connected at the “tee” location in Fig. 8. Figure 9 shows a comparison of the impedances measured and calculated looking from the tee towards the chuck and from the tee towards the rf generator. As can be seen, the chuck circuit was well fitted using an inductance of 94.6 nH and a capacitance of 364 pF. The impedance of the rf generator, matching network and cable are in reasonable agreement with the model except near the operating frequency. That discrepancy is likely due to the measurements being made with all reactor power off. That condition meant that the two variable inductors in the match, which were electrically tuned saturable reactors, had inductance values that differed from operating conditions.

The calculation of chuck potential waveform was performed by direct integration in time of the set of differential equations describing Fig. 8 and the plasma sheath. As each calculation proceeded, the variable inductors in the matching network were adjusted to minimize the reflected power at the fundamental excitation frequency. Computational stability problems were not encountered provided that the inductances were adjusted slowly. Typically, steady-state conditions were achieved after several hundred cycles and the reflected power was essentially zero. Figure 10 shows the chuck potential waveform computed for the standard conditions without control of harmonics. Parameters of the computation are noted in the caption. The overall shape of the computed waveform
agrees quite well with that measured in Fig. 2. We found that the computed peak chuck potential varied inversely with electron density, but the overall waveform shape was not particularly sensitive to the assumed values of electron density, temperature, or ion mass.

In order to compute a particular case of active or passive modification of harmonics, the appropriate switches in Fig. 8 must to be thrown and the three tuned circuits must be set to the proper conditions. Subsequently, the calculation proceeds as in the case above without harmonic modification. Computationally, this procedure was successful and it demonstrated the capability for making major changes to the chuck waveform by tuning the auxiliary circuits. However, we never were able to determine settings for the tuned circuits that produced a waveform similar to that shown in Fig. 4. Due to time constraints on the experiment, we did not obtain a sufficient set of experimental impedance measurements to unravel this problem. The main experimental impedance feature that we noted during the experiment was that the waveform of Fig. 4 was accompanied by an impedance zero in the passive-tuning circuit near the second harmonic. A computational investigation of that condition produced waveforms that were greatly different from Fig. 4.

This outcome of the computations was not satisfying. The agreement of the model with the standard reactor configuration and the previous success of the model3 lend credibility to the general approach. The failure to find conditions corresponding to Fig. 4 suggests that we overlooked something significant in either analyzing the experiment or in executing the model. This remains unfinished business.
VI. SUMMARY AND CONCLUSIONS

We successfully demonstrated two techniques to modify greatly the waveform of the chuck potential of a high-power industrial plasma-etching reactor. The change in potential waveforms indicated that the majority of the ion energy distribution function was shifted to much higher energies without changing the power delivered by the rf generator. The modified waveforms produced changes in etching that we do not understand, but we did not optimize new recipes to take advantage of modified ion distributions. The procedures and hardware used to modify the chuck potential waveform did not upset the normal functioning of the reactor in any way that was noticeable to the operator.

A first-principles model was developed based on earlier similar work to describe the harmonic-generation process at the chuck. The model was successful in describing the standard reactor configuration but it was not successful in describing the experimental cases with modified harmonic content.

Further work in this area could focus on taking advantage of the capability to modify the ion distribution function by applying it to a process for which it is beneficial. In addition, improved experimental diagnostics would help in understanding the complex nonlinear system and in developing a predictive model. These diagnostics could include complete impedance characterization of the auxiliary tuned circuits, measurement of the chuck current, measurement of temporal variations in the plasma potential, and direct measurement of the ion energy distribution function.
It is worth pointing out a relationship of this work to tool design. We demonstrated clearly that a change to the passive rf circuits in the chuck of a production reactor can have a dramatic effect on the chuck potential waveform. This modification presumably changes the ion energy distribution function and, consequently, changes process performance. In our work, we made intentional controlled impedance changes. However, unintentional uncontrolled changes to inductance or capacitance in the chuck circuit could have equally important effects on process performance. Moreover, when a tool is first designed, the selection and layout of components determines the impedance characteristics of the chuck circuit, which affects the chuck waveform. Consequently, the design process effectively selects a waveform from a large set of possibilities, and this selection is frequently done accidentally, without planning. Subsequently, process development must proceed constrained by this unplanned narrowing of possibilities. There may be a better way.

Acknowledgments

We are grateful to Ashley Taylor who provided the wafer samples and to SEMATECH who gave us unfettered access to their tool. We also are grateful for the support of Gil Yetter and the Calibration Laboratory at SEMATECH which were instrumental in the execution of this experiment.

We appreciate the support of this work in part by the U.S. Department of Energy under contract AC04-94AL8500 with Sandia. Sandia is a multiprogram laboratory operated by the Sandia Corporation, a Lockheed Martin Company, for the United States
Department of Energy.
Table captions

1. Standard etching conditions.

2. Recipe modifications. The $C_2F_6$ percentage is the change relative to the standard recipe in Table 1.
<table>
<thead>
<tr>
<th>Step Name</th>
<th>Source Power (W)</th>
<th>Bias Power (W)</th>
<th>Ar (sccm)</th>
<th>$\text{C}_2\text{F}_6$ (sccm)</th>
<th>$\text{O}_2$ (sccm)</th>
<th>Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARC Etch</td>
<td>2600</td>
<td>150</td>
<td>75</td>
<td>30</td>
<td>25</td>
<td>30</td>
</tr>
<tr>
<td>Main Etch</td>
<td>2800</td>
<td>1400</td>
<td>95</td>
<td>40</td>
<td>--</td>
<td>60</td>
</tr>
<tr>
<td>Transition</td>
<td>2800</td>
<td>1400</td>
<td>95</td>
<td>40</td>
<td>90</td>
<td>5</td>
</tr>
<tr>
<td>PR Strip</td>
<td>2800</td>
<td>300</td>
<td>--</td>
<td>--</td>
<td>250</td>
<td>40</td>
</tr>
</tbody>
</table>

Table 1
Berry et al.
JVST A
<table>
<thead>
<tr>
<th>Case</th>
<th>$[C_2F_6]$ (%)</th>
<th>Total Flow (sccm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>15</td>
<td>135</td>
</tr>
<tr>
<td>B</td>
<td>30</td>
<td>135</td>
</tr>
<tr>
<td>C</td>
<td>60</td>
<td>135</td>
</tr>
<tr>
<td>D</td>
<td>30</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 2
Berry et al.
JVST A
Figure captions

1. Diagram of the hardware used to test active and passive harmonic control. The top row of components is part of the normal reactor system. The three parallel-resonant L-C circuits are used for both active and passive control. The switch symbolically enables and disables the active-control part of the circuit.

2. Measured chuck potential waveform of the unmodified reactor showing nonsinusoidal behavior, i.e. significant harmonic content. The unknown dc offset in the figure has been set to be consistent with the estimated plasma potential $V_p = +20$ V, which is indicated by the dashed line. This choice is not critical for our analysis.

3. Potential spectra computed from the data in Fig. 2. The top graph shows the raw spectrum and the bottom graph shows the cumulative (integrated) spectrum. To the extent that $V_p$ in Fig. 2 is accurate and the ion current is approximately constant in time, these potential spectra would correspond directly to ion energy distribution functions. This interpretation suggests that fewer than 30% of the ions have energy above 100 eV.

4. An example of a modified chuck-potential waveform. This particular example was obtained under passive control and was adjusted as in Fig. 2. Similar waveforms were also obtained under active control.
5. Potential spectra computed from the data in Fig. 4. These spectra were computed assuming a constant $V_p$ slightly above the positive peaks in Fig. 4. The cumulative spectrum suggests that 50% of the ions had energies in excess of 400 eV.

6. SEM micrographs of wafers etched with the baseline recipe listed in Table 1. 6A, 6B and 6C resulted from a standard chuck waveform and 6D, 6E and 6F from a modified waveform. Nominal feature sizes were 250 nm (6A and 6D), 400 nm (6B and 6E) and 500 nm (6C and 6F).

7. SEM micrographs of wafers etched with modified recipe "C" (as listed in Table 2). 7A, 7B and 7C resulted from a standard chuck waveform and 7D, 7E and 7F from a modified waveform. Nominal feature sizes were 250 nm (7A and 7D), 350 nm (7B and 7E) and 400 nm (7C and 7F).

8. Schematic diagram used in the modeling of the reactor. For simplicity, this diagram omits resistors that were in series with each inductor to represent circuit losses, and the diagram omits some parasitic inductances and capacitances that were included in the auxiliary tuned circuits.

9. Comparison of measured and computed impedances looking from the tee in Fig. 8 towards the rf generator (left) and towards the chuck (right). The dots are measured values and the smooth curves are computed values. The measurements were made with all reactor power off. Consequently, the inductors in the matching network, which were electrically tuned, did not have inductance values corresponding to normal operating conditions. That may be a source of the disagreement at low frequency in the left graph.
10. Computed chuck potential waveform for the standard reactor without modification of the harmonics. The dashed line is the computed plasma potential. This waveform is to be compared directly to Fig. 2 that shows the measured chuck potential. For the calculations, we assumed electron temperature = 3 eV, ion mass = 50 (e.g. CF₂⁺), and the chamber dimensions corresponded to measured sizes. The electron density was set to 8 x 10¹¹/cm³ so that the peak chuck potential matched the measured value (-625 V) at 1400 W.
Fig. 1
Berry et al.
JVST A
Fig. 2
Berry et al.
JVST A
Fig. 3
Berry et al.
JVST A
Fig. 4
Berry et al.
JVST A
Fig. 5
Berry et al.
JVST A
Fig. 8
Berry et al.
JVST A
Fig. 9
Berry et al.
JVST A
Fig. 10
Berry et al.
JVST A
References


