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Electrical characterization of rf plasmas

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ABSTRACT

Radio-frequency (rf) electrical sources are commonly used to generate plasmas for processing of industrial materials and for related experimental work. Published descriptions of such plasmas usually include generator-power measurements, and occasionally include plasma dc-bias measurements. One or both of these quantities are also used in industrial feedback control systems for setpoint regulation. Recent work at Sandia and elsewhere with an experimental rf discharge device (the "GEC RF Reference Cell") has shown that power and dc-bias levels are often insufficient information for specifying the state of the plasma. The plasma can have nonlinear electrical characteristics that cause harmonic generation, and the harmonic levels can depend sensitively on the impedance of the external circuitry at harmonic frequencies. Even though the harmonics may be low in amplitude, they can be directly related to large changes in plasma power and to changes in optical emission from the plasma. Consequently, in order for a worker to truly master the plasma-generation process, it is necessary to understand, measure, and control electrical characteristics of the plasma. In this paper we describe techniques that have been developed from work with the Reference Cell for making electrical measurements on rf plasmas, and we describe surprising observations of harmonic behavior.

1. INTRODUCTION

Historically, differing results have been obtained by workers at different laboratories from experiments with rf-excited processing plasmas that were thought to have similar characteristics. This suggests that there may be hidden variables that are not understood nor documented by many groups. This situation hinders progress in understanding and controlling plasmas for industrial applications. An ad-hoc group of participants of the Gaseous Electronics Conference agreed to establish a discharge cell (the "GEC RF Reference Cell") as a reference system to enhance interlaboratory comparisons. The consensus design is a parallel-plate system that has good diagnostic access, can achieve high-vacuum conditions, is compatible with reactive gases and wafer processing, and is relatively inexpensive. The GEC Cell has a stainless-steel body, "showerhead" gas injection, and 4"-diam aluminum electrodes excited at 13.56 MHz. The interior geometry of the Cell is symmetric, but most workers power one electrode and ground the other, so that asymmetric operation (standard industrial practice) is achieved. GEC RF Reference Cells were operational at many laboratories in 1990 and measurements have been reported by several groups. 1, 2, 3, 4, 5, 6

In order to determine whether or not GEC Cells at different laboratories perform similarly, the collaborating groups agreed to measure and compare the voltage-current (V-I) characteristics at the first five harmonics of the drive frequency for discharges in argon at pressures from 0.1 to 1 Torr.

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The groups felt that V-I comparisons would be a good starting point for characterizations because those comparisons would be easier and less expensive for all to perform than alternatives such as electron-density measurements or quantitative optical-emission measurements. The workers thought that agreement in V-I data was a necessary condition for achievement of similar plasmas. Of course, agreement in V-I data does not guarantee that the plasmas are identical. As a result of this work, a variety of experimental and analytical methodologies have been developed that have been shown to be applicable to industrial reactors as well as to laboratory plasma systems. In this paper we summarize several of those techniques as applied to the GEC Cell. First, we describe V-I measurement techniques and problems, and then we use equivalent-circuit models to convert measured V and I to plasma V and I. Next, we describe nonlinear interactions between the plasma and the external electrical circuit that provides the rf excitation to the plasma. Finally, we present selected data on harmonic behavior that indicate the richness of nonlinear phenomena that can occur in rf discharges.

2. V-I MEASUREMENT

V-I measurement begins with voltage and current probes (sensors). Most of the initial data from the GEC Cell were taken with commercial probes. Their use is advantageous because they are relatively inexpensive and readily available to all collaborating groups. In order to obtain accurate, absolute measurements of voltage and current, one must determine amplitude and phase responses of the probes as functions of frequency. Absolute accuracy is perhaps not important in some applications, such as control systems where one needs only a relative signal that is reproducible from run to run. However, accuracy is certainly important in comparing GEC-Cell data between groups unless all groups use probes with identical errors. Accuracy also might be useful in control systems so that information from different reactors and information gathered over a long time period could be used, for example, to identify hardware, recipe, or gas-flow differences.

As an alternative to the commercial probes, we developed "derivative" probes as shown in Fig. 1 to measure voltage and current. This technology is based on similar techniques used in other areas of physics and engineering.^{7, 8} These probes are advantageous because their components are rugged and very inexpensive, they have perfect linearity and excellent frequency response, and they are very compact. Their main disadvantage is that they need amplitude calibration (unless special procedures are used in design and fabrication). Calibration often is performed at low frequency by reference to a calibrated commercial probe.

These probes function as follows. The derivative voltage probe has a pickup element that is capacitively coupled to the power lead, but the pickup element is held close to ground potential because it is connected to ground by a "low" terminating resistance ($R_t = 50 \Omega$ in Fig. 1). A capacity C_c couples the pickup element to the power lead and a stray capacity C_s couples the element and ground. The pickup element's voltage V_p and the voltage of the power lead V are related to a displacement current I_p to the probe by $I_p = C_c d(V - V_p)/dt$. If the time constant $R_t C_s$ is much shorter than times of interest, then I_p will flow through R_t and $V_p = I_p R_t$. If the time constant $R_t C_c$ is similarly short (0.15 ns in Fig. 1), then $V_p \ll V$, and we obtain $V_p = R_t C_c dV/dt$. Thus the probe's voltage is proportional to the derivative of the voltage on the power lead.

The derivative current probe works in a related manner. The probe has a conducting loop of self-inductance L_p located near the power lead. This loop has a "high" terminating resistance ($R_t = 50 \Omega$ in Fig. 1) that prevents significant current flow in the loop. Here, 50Ω is a "high" resistance in the sense that the time constant L_p/R_t is much shorter than times of interest. In this case, the flux Φ through the loop is due to current flow I in the power lead, and is numerically related by $\Phi = MI$, where M is the mutual inductance. Since the voltage V_p across R_t is given by $V_p = d\Phi/dt$, we obtain $V_p = M dI/dt$. Thus the probe's voltage is proportional to the derivative of the current in the power lead.

There are several features to note in using derivative probes. First, these probes do not detect the dc components of voltage or current. DC voltage must be obtained from another source such as a high-impedance resistive divider with capacitive filtration. Of course, dc current is not present if the rf source employs a blocking capacitor, as is commonly the case. Second, the probes' relative outputs increase with frequency. That is, in terms of complex variables, the voltage signal is proportional to $j\omega V$ and the current signal is proportional to $j\omega I$. To obtain the correct harmonic signals, one can divide by $j\omega$ in the frequency domain after performing Fourier transforms. One could use a hardware integrator, but the resulting signal levels might be inconveniently low. The $j\omega$ factor is a minor complication, but it also presents an advantage of these probes over more-conventional probes. Since the output increases with frequency, the signal-to-noise ratio of the harmonics is improved, and thus the harmonics can be measured more accurately even though they may have low amplitudes.

Amplitude calibration of commercial and derivative probes can often be performed using a signal generator and a calibrated dual-channel oscilloscope. Approximate phase calibration for some GEC-Cell work was performed on voltage and current probes taken in pairs. For calibration, the probes pairs were used to measure voltage and current at a point in a circuit that had a reactive impedance, and thus a known phase relationship ($\pm 90^\circ$). The probes were installed for use with the GEC Cell, but no discharge was ignited. Instead, the Cell was excited by a low-voltage pulse train from a signal generator. The resulting signals were Fourier analyzed. At all the harmonics, any computed phase deviation from $\pm 90^\circ$ represented a phase error, since the Cell presented either a capacitive or an inductive load, depending on frequency. Measurements on one Cell showed that resistive losses would need to be considered to obtain phase accuracy better than 1° . With one pair of commercial probes, we measured phase errors in the 10- to 70-MHz range of 10° to 50° , whereas the derivative-probe pairs were accurate to 3° . (These error values include intrinsic probe errors, errors due to omission of resistive corrections, and quantization errors that occur in the digitization process.) Once amplitude and phase errors are known, they are removed computationally during the data-analysis process.

As a result of employing such procedures, the initial plasma measurements obtained with the GEC Cell are thought to have absolute accuracy of several degrees in phase and perhaps $\pm 10\%$ in amplitude at the fundamental and first two or three harmonics. To this level of accuracy, the Cells at different laboratories have similar dc bias and similar V-I characteristics at the fundamental frequency.^{1, 4, 5} The harmonics generally are not in good agreement, as will be discussed below. The V-I phase angle of the fundamental in argon discharges often exceeded -80° . As a result, power computations, which depend on the cosine of the phase, were quite sensitive to phase errors. For example, a 2° error at -85° causes a 40% error in power computation. Discharges in electronegative gases such as Cl_2 gave phase angles

then the total input impedance will be very high at the frequency of resonance. Consequently, the input current will be near zero in the absence of a plasma discharge, and the input current in the presence of a discharge will be directly proportional to the plasma current.

This "shunt-circuit" technique has been successfully applied to GEC Cells at many laboratories to improve measurement accuracy. The reader is referred to Refs. 3-5 for detailed discussions of shunt circuits and determination of component values. Note that the shunt functions as described above at only one frequency, which is normally selected to be the fundamental. Note also that we have neglected resistive losses in the above discussion. In practice, shunt coils often are fabricated from coil stock that employs #10 wire and there are resistive losses that cause the measured current to be nonzero when the shunt is tuned to resonance. In one case, the measured current with the shunt was 0.5% of the current without the shunt (no discharge) and the overall Q (quality factor) was 216. The calculated circuit resistance was less than $1\ \Omega$, which was consistent with values from skin-depth calculations. For precise analysis, one must take such resistive effects into account, particularly as they affect computed phase angles. A $1\text{-}\Omega$ error can lead to a 10° phase error for computed impedances near $100\ \Omega$. In typical low-power operation of the GEC Cell, rf currents are approximately 1 A. This leads to resistive losses (I^2R) in the 1-W range, which pose no thermal-dissipation problem. However, if this shunt-circuit technology were applied to a low-impedance industrial reactor drawing 10 to 20 A, then one would need to consider lowering the resistance and adding active cooling to the shunt circuit.

The equivalent-circuit model of Eqs. 1 and 2 is a simple representation of the GEC Cell. Other, more complete models have been proposed³ that treat internal details of the Cell. In ongoing work, Prof. J. T. Verdeyen, University of Illinois, has been studying the adequacy of such models by performing a frequency-dependent impedance analysis of various parts of the Cell. Using a vector impedance meter, one can measure the variation of reactance with frequency and derive circuit models that match the observed behavior. This technique appears to be an effective technique for modeling laboratory plasma devices and also should be valuable for analysis of industrial systems.

4. NONLINEAR EFFECTS

In the beginning of the GEC-Cell collaboration, we were not certain that it was necessary to go to the trouble and expense to standardize all the components used to generate the rf power. Consequently, the participating groups used different rf apparatus to take their initial data. Drive conditions were standardized by specifying the peak-to-peak voltage to be achieved at the measurement point by whatever rf-generation system was chosen. Experimental results have since shown that the harmonic content of the voltage and current of the GEC Cell are greatly affected by changes in rf generator, matching networks, and cable lengths. In a collaboration with the group under Prof. H. Anderson at the University of New Mexico, this effect was shown dramatically.⁹ When the rf generator was changed from one brand to another, neither of which generated significant harmonics by themselves, the fundamental components of voltage and current remained almost unchanged. However, the second harmonics of voltage and current changed greatly and the optical emission from the plasma in the 750-nm to 850-nm region decreased by approximately 43% ! This is a strong indication that the chemistry of that particular argon discharge changed substantially due to changes in the shape of the electron distribution function and/or due to changes in the electron density. Obviously, the harmonics

The plasma is the source of the harmonics and the harmonics interact only with the circuits downstream of the filter. As a result of this arrangement, we see that the magnitude of the plasma voltage-to-current ratio of each harmonic must equal the magnitude of the impedance of the circuit connected to the plasma. Consequently, we can adjust the V-I ratio of the plasma's harmonics by tuning the external circuit shown in Fig. 2. Also note that since the filter is nominally non-dissipative as are the other circuit elements in Fig. 2, the external circuit impedance is purely reactive. This means that the V-I ratio of the harmonics is also purely reactive and thus there can be no net power in the harmonics with this circuit.

Figure 3 shows measured magnitudes of the frequency components of voltage and current as a function of the cable length connecting the filter to the GEC Cell, for discharges in argon at 100 mTorr with 200 V peak-to-peak excitation. The voltage 2nd harmonic approaches 40% of the fundamental under some conditions, but generally is much lower. The dc bias is very sensitive to small changes in cable length at critical points, but otherwise varies smoothly. The current harmonics are generally large, with the 2nd and 3rd harmonics nearly equaling the fundamental under certain conditions. Periodicity in the structure of Fig. 3 is evident: most periods correspond to changes in cable length that equal $\lambda/2$ at the particular frequency. There also appear to be interactions between harmonics that don't follow such a simple pattern. Figure 4 shows the plasma impedances Z1 and Z2 computed from the data in Fig. 3 and the calculated circuit reactances, for the 2nd and 3rd harmonics. There is excellent agreement between the data and calculations, which supports the observations in the preceding paragraph.

Effects similar to the ones described here occur even when a low-pass filter is not present because the same basic principles apply. A system without a filter may be more difficult to analyze, however, because the impedance at the harmonic frequencies of the rf generator and matching network may not be known.

It is not yet clear how to apply the harmonic information to improve industrial processes. In other experiments we have seen evidence that patterns of harmonics may be valuable in fingerprinting a particular process. Consequently, on-line analysis of those patterns might be used to achieve and/or detect deviations from the proper process trajectory. We also note that plasma modeling will be incomplete until it is capable of addressing the type of nonlinear circuit interactions seen here.

6. CONCLUSIONS

V-I measurements with the GEC RF Reference Cell were initiated to establish a simple, affordable, minimal diagnostic set to ensure similar operation of Cells at different laboratories. The initial diagnostic work was largely successful and led to the realization that V-I signals were richer in content than many workers had anticipated. Subsequent work has shown that the harmonics can affect plasma properties to an important degree. Efforts at improving the accuracy of V-I diagnostics are continuing. There also remains a need for Cell users to standardize the impedance characteristics of the rf circuitry in order to achieve agreement in harmonic data. We have demonstrated a filter methodology that isolates the plasma from changes in the upstream rf circuitry and thus could be refined and adopted as a standard for the Cell. While V-I diagnostics cannot provide the detailed plasma information available

were truly important in certain cases, and some form of standardization of the rf circuitry was needed for the GEC Cell.

We reasoned that the above effects must be due to some phenomenon associated with the intrinsic nonlinearity of the plasma. Since a major manifestation of the plasma nonlinearity was harmonic generation by the plasma, it seemed that the harmonics must be interacting with the rf generator. By using a low-pass rf filter placed close to the Cell in the rf-power lead, we prevented the interaction of the Cell-generated harmonics and the rf circuitry (including generator, matching network, and cable) that was upstream of the filter. The rf filter was a lossless passive network¹⁰ that reflected signals at the second harmonic and higher but allowed transmission at the fundamental frequency. Subsequent tests showed that the filter successfully eliminated all dependence of plasma parameters on rf circuits upstream of the filter. In this work, as before, the plasma excitation was controlled by specifying the peak-to-peak voltage at the measurement point, which was downstream of the filter.

As a result, it appears unnecessary to standardize the entire rf-generation system in order to obtain uniform operation of GEC Cells at different laboratories. Instead, one can standardize the rf filter and the circuitry downstream of the filter. This less expensive approach will likely be the thrust of future work with the GEC Reference Cell.

The filter technology can also be considered for industrial applications. The use of an rf filter would isolate the reactor from changes in cable plant, rf generator, and matching network. If one changed cable lengths, brands of rf generator, or tuning of the matching network, the plasma processing would not be affected. This would be true provided that the plasma excitation level were controlled with reference to a voltage or current level measured downstream of the filter, as has been done with the GEC Cell. A derivative probe, as advocated above, could be used as the sensor for this control loop. One can speculate that a filter would stabilize a process and reduce long-term process variations, but actual correlations to improved product have yet to be demonstrated.

5. HARMONIC SPECTRA

In a single plasma V-I measurement with the GEC Cell, one typically obtains magnitude and phase data for five voltage and five current harmonics, and the value of dc bias. This yields 21 (real) numbers. Although some of the higher harmonics may be low in magnitude and thus of little immediate interest, there is still a lot of information to compare and digest. Here, we present selected data from the GEC Cell concerning only one aspect of the harmonics.

The rf-filter technology described in Section 4 provides a means for standardization of rf circuitry of the GEC Cell. In developing a filter, we connected it to the GEC Cell with a length of coaxial cable, and we found that the harmonic amplitudes were quite sensitive to changes in the length of that cable. Figure 2 shows an equivalent circuit of the GEC Cell, cable, and filter at frequencies above the fundamental drive frequency. Since the filter reflects signals at these higher frequencies, the rf generator, matching network, and cables that are upstream of the filter do not appear in this equivalent circuit.

from many other techniques, they seem to constitute an untapped, inexpensive, and robust method to gather much information that might be useful for monitoring and controlling industrial plasma processes.

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Fig. 1. Schematic diagram of derivative probes. The capacitive voltage probe consists of a metal tube that surrounds the rf power lead and is separated from it by insulation. The inductive current probe is a loop of insulated wire placed adjacent to the power lead so that magnetic flux from the rf current threads the loop. Typical dimensions, coupling factors, and sensitivities are indicated. Note that the current probe is shown in a mechanically convenient orientation so that it is very close to the voltage probe. However, this orientation will give an inverted signal that can be inverted again by hardware or software, if desired.

Fig. 2. Model of the rf circuitry for harmonics. The plasma is powered by 13.56-MHz excitation. The plasma generates the harmonics which are confined by the low-pass filter to the region shown in this drawing. The filter constitutes a load that has a frequency-dependent reactance. As far as the harmonic wave flow is concerned, the rf generator and matching network don't exist. Since the elements shown are lossless, the net harmonic power must be zero.

Fig. 3. Spectra of voltage and current magnitudes. These data represent amplitudes of the various harmonics of plasma voltage and plasma current for argon discharges at 100 mTorr with the excitation held constant at 200 V peak-to-peak at the measurement point. The abscissa is the length of cable shown in Fig. 2.

Fig. 4. Plasma and circuit impedance magnitudes. The data points are the V-to-I ratios for the 2nd- and 3rd-harmonic data in Fig. 3. The line is the impedance of the circuit shown in Fig. 2 looking away from the plasma as calculated by M. Kamon. His calculation used transmission-line equations and used actual circuit values for the Cell and the filter, without adjustable parameters. Fourth-harmonic data also agree well with the calculation.

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