Stabilizing RF Generator and Plasma Interactions

V. Brouk and R. Heckman, Advanced Energy Industries, Inc., Fort Collins, CO

Key Words: Stability, Process control, RF power, Semiconductor etch

ABSTRACT

Reduced semiconductor feature size generally requires etch processes to operate into lower pressure regimes, often at relatively low RF power levels. Plasma impedance is dependent upon both the process conditions and the power level. Changes in plasma impedance are generally more dynamic at lower output powers as compared to higher power levels. In low pressure, low power process regimes, interactions between the power-dependent plasma impedance and load-dependent RF delivery system can create notable instabilities, often resulting in severely unstable voltage oscillations within the plasma. The power supply and impedance matching control loops are often unable to counteract these instabilities, resulting in uncontrollable and unrepeatable variations in process parameters. In this study we look at how the characteristics of the plasma processing system and the RF delivery system can interact to influence the stability of the plasma. A means for quantifying the stability factor for the combined generator and plasma system will be shown. This study will review a few methods for configuring the RF delivery system and plasma processing system for stable operation.

INTRODUCTION

RF power delivery systems are one of the most important and delicate parts of the semiconductor etch manufacturing tool. RF generators are generally designed independent of the tool with their primary requirement being power delivery. Instabilities in plasmas have been thoroughly investigated, and in most of these works, special measures were taken to isolate the RF generator from the plasma in order to reduce or eliminate the RF system's contribution to the instabilities.

The most frequent instabilities occur in etching tools during processes that utilize electronegative gases, e.g. O_2, SF_6, CF_4, at relatively low pressure, typically 5 - 150 mTorr, and at low RF output power, generally in the range of 20 - 500 W. Instabilities are observed in reactors with both capacitive [1] and inductive [2,3] discharges.

The trend in the semiconductor industry to process smaller geometries often results in recipes being run at lower RF output power into lower pressures. Both factors prove to increase the probability of unstable behavior.

The trend in RF power supply design is to reduce the package size for ease of tool or chamber mounting. This generally has favored the utilization of high-efficiency switch-mode amplifier topologies for higher power density packaging. As a general matter, tools and processes that employ modern switch-mode power supplies are found to be more susceptible to plasma instabilities under the above mentioned process conditions. Transmission line length has long been recognized as a handle to expand the area of stable system operation. Some degree of deliberate matching network mismatch was also found, in some circumstances, to reduce the probability of plasma instabilities. Chamber mounted generators that utilize advanced matching techniques, eliminate both the variable match network and interconnecting transmission line, and therefore the more convenient handles for reducing instabilities.

Multiple observations have been made that the same process in the same reactor can be either stable or unstable, depending on the type of RF power delivery system, even though these RF systems are inherently stable when operated into a linear load. Recognizing the dynamic interaction between the RF system and the plasma, it has become clear that the optimum RF powered plasma requires that the interactions between the RF delivery system and the plasma be understood and taken fully into account. Some systems today are designed to take advantage of the particular dynamics of the process power supply, and consider the RF generator and its load, the plasma, as a single system.

Understanding the RF-plasma interaction becomes critical, and this paper is devoted to the analysis of the interaction in purely electrical terms. The plasma is considered as a non-linear electrical object in a macro time scale; that is, its impedance averaged during the RF cycle is the function of the power delivered to the plasma. No consideration is given to the non-linear effects within a single RF cycle, even though it is recognized that some second order effects can be attributed to the harmonics. This approach allows limiting the scope to the fundamental frequency phenomena only, while giving useful practical results. It is beyond the scope of this paper to address instabilities that do not involve interaction with the RF system. With such an approach, the system behavior can be predicted based on some means to quantitatively compare

 505/856-7188 ISSN 0737-5921
47th Annual Technical Conference Proceedings (April 24–29, 2004) Dallas, TX USA

RF systems and to measure such system parameters as stability margin and natural frequency for small perturbations.

SYSTEM INSTABILITIES

Most of the experimental work was conducted on the plasma chamber with inductively coupled plasma, using SF_6, sometimes diluted with argon, while etching tungsten. This type of process was chosen due to its characteristically unstable system performance and its acute sensitivity to RF system parameters. The setup is not unlike a commercial plasma etch tool. Figure 1 shows its simplified block diagram.

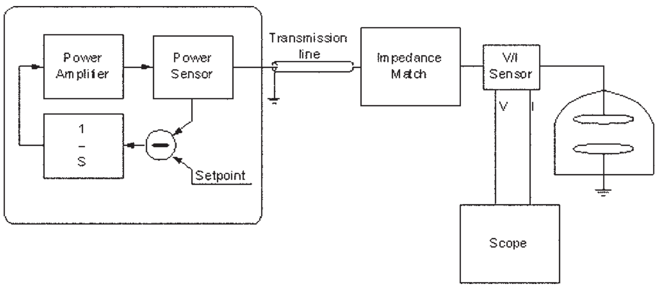

Figure 1: Simplified block diagram of RF delivery system and plasma chamber.

For electrically non-intrusive instability observations, a V/I sensor was installed at the chamber electrode input with its V/I samples monitored with an oscilloscope. The RF generator control circuitry maintains a constant forward or delivered (load) power, depending on the test conditions. The maximum loop bandwidth is typically limited between 5-50 kHz.

For the purpose of this paper, the generator/plasma instability is considered to be slow if the entire spectrum of the RF envelope falls inside the generator loop bandwidth; otherwise it is considered to be fast. The reason for such a distinction is that the generator reaction to the impedance disturbance is completely different for these two operating regimes. The three different instability types observed are shown in Figure 2. The envelope on 2a is nearly sinusoidal at ~1.5 kHz, i.e. slow. Both Figures 2b and 2c are the examples of a fast instability. Even though the repetition rate on 2c is only 3 kHz, its spectrum is close to that of 2b, because of the fast transitions between states, which occur outside of the operating control bandwidth of the generator.

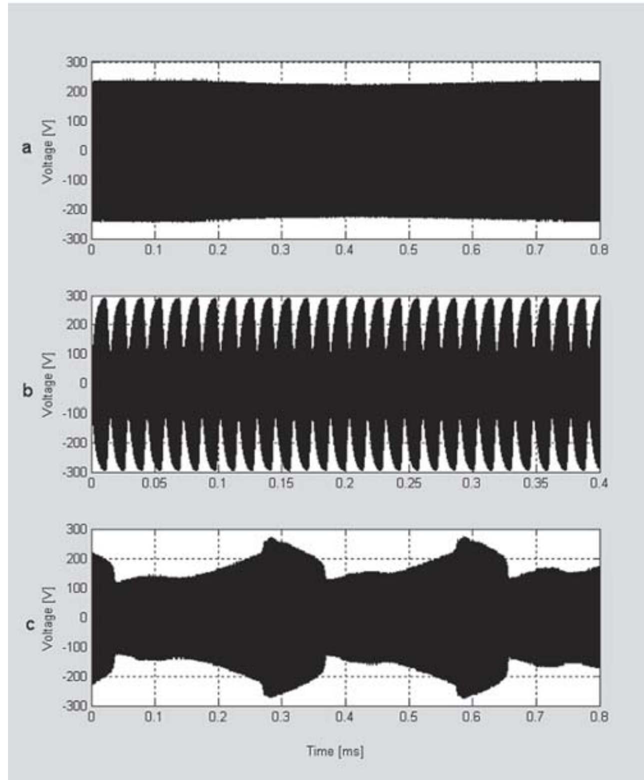

Figure 2: Three different instability types.

The electrical interaction between the RF system and the plasma is illustrated in Figure 3. The RF system is delivering power P_0 while the plasma imposes the impedance Z_0 at the generator terminal. The plasma responds to the delivered power disturbance dP with the change of its impedance dZ, and the RF system responds to the impedance change of dZ with the power change of dP. Clearly, a closed-loop system exists, including both the RF system and the plasma load, which depending upon the gain or phase margin, can be stable or unstable. The normalized gains of the two system components can be defined by how they respond to both power and impedance changes. The two system components gains are:

$$G_{RF} = \frac{dP/P_0}{d\overline{Z}/Z_0}$$

Equation 1a

$$G_{plasma} = \frac{d\overline{Z}/Z_0}{dP/P_0}$$

Equation 1b

In this definition, Z_0 is the steady state impedance at the generator terminal, most commonly Z_0=50 Ohm. It is very important to note that dZ is a complex value or vector on a Smith chart, consequently its angle, or direction, may be essential for instability analysis. The system will be unconditionally stable for any angle if the condition below is satisfied:

$$|G_{plasma}| \times |G_{RF}| < 1$$

Equation 2

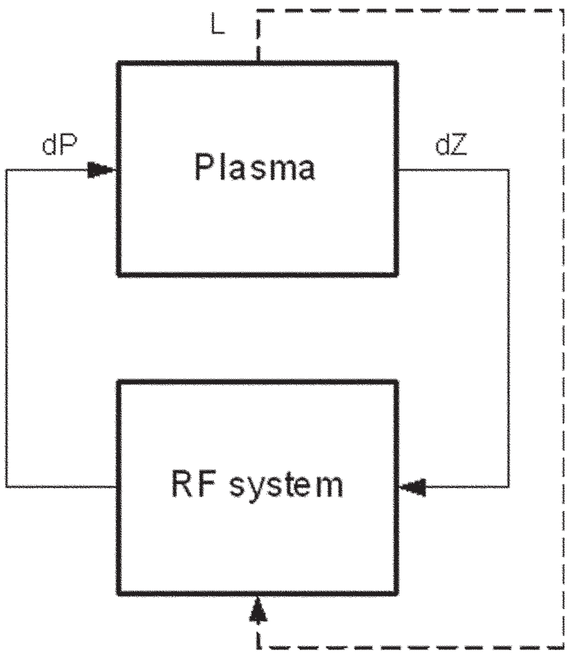

Figure 3: Plasma - RF system interaction.

Stabilizing the marginally stable system naturally starts within the system itself. However, it is recognized that stability can also be influenced external to the system. This is also shown in Figure 3, where the dashed line on the graph illustrates a possible external feedback path for active instability dampening. D.L. Goodman and N.M.P. Benjamin [5] describe successful use of a light sensor (L) and wide-band amplifier for active dampening.

Slow Instabilities

In order to measure the system stability, a small disturbance is applied to the RF generator power control loop and the output power response is measured. In this experiment, both the disturbance and the means to measure the power response are generated within the power supply. Figure 4 shows a 10% disturbance in RF power (a), the response of a stable system (b) and less stable system (c). The only difference between (b) and (c) is that SF_6 pressure was dropped from 20 to 5 mTorr.

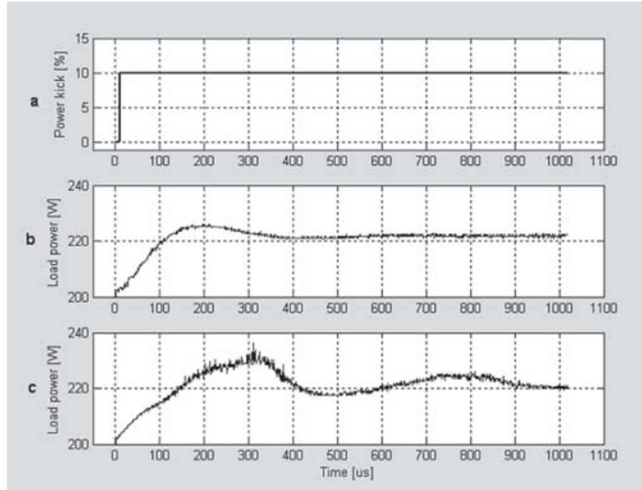

Figure 4: Active excitation of slow instability.

Given that the generator's loop frequency response is known, this data allows calculating the first order plasma transfer function and other important system parameters, including natural frequency, damping factor, and stability margin. Even though these parameters are applicable for constant conditions and small disturbances only, they can be used to quantify the stability factor for any plasma system, whether utilized as a means to baseline a tool or process, or to track how these conditions change over time during the manufacturing process.

One of the possible slow instability mechanisms was numerically modeled and is illustrated below. Figure 5 is a Smith chart, representing a conventional impedance matching process, when the plasma impedance is tuned to 50 Ohms.

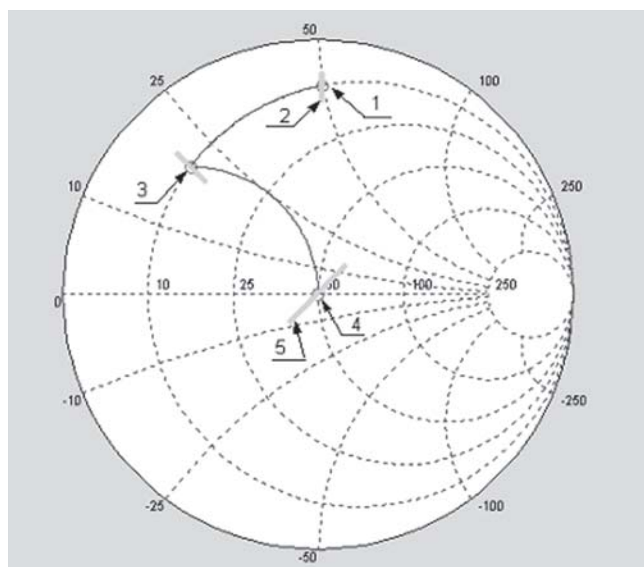

Figure 5: Impedance matching and trajectory transformation.

Circle 1 represents a steady-state plasma impedance. The initial disturbance was modeled as a sinusoidal deviation of the reflection coefficient, which is illustrated as an impedance trajectory 2 on the graph. The series matching element of a conventional L-type match topology moves the impedance 1 to circle 3, and the shunt matching element moves circle 3 to the Smith chart origin of 50 ohms, represented by circle 4. Through this impedance transformation, trajectory 2 is transformed into trajectory 5, and it is located almost symmetrically with respect to the origin.

Figure 6 shows the operation of the RF system in this case, assuming that the generator loop maintains constant forward power. Trace "a" shows initial impedance disturbance, traces "b" and "c" show reflected and delivered power, respectively. One can see that the delivered power deviation occurs at the second harmonic of the disturbance frequency. More accurate analysis shows some amount of the fundamental disturbance frequency, which is explained by nonlinearity at the Smith chart periphery. For extremely small disturbances and a perfect match, the fundamental frequency effectively disappears.

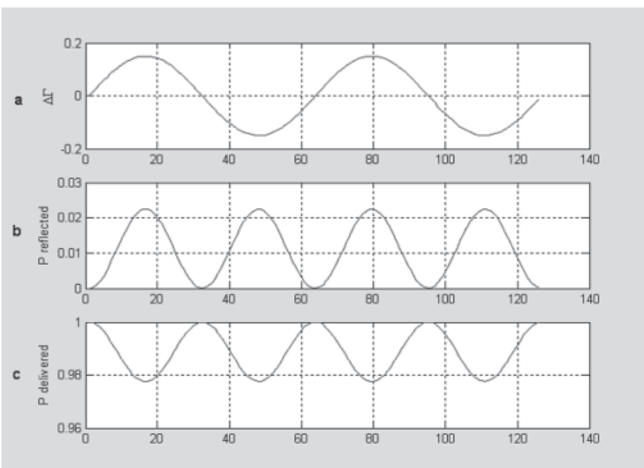

Figure 6: RF system operation (50 ohm impedance match).

This operating scenario changes dramatically in the presence of a mismatch, which is shown in Figure 7. In this case, the same steady-state impedance shown in Figure 5 is tuned to two different near-50 ohm impedances, cases 1 and 2, which were created by a small deviation in the series match element value.

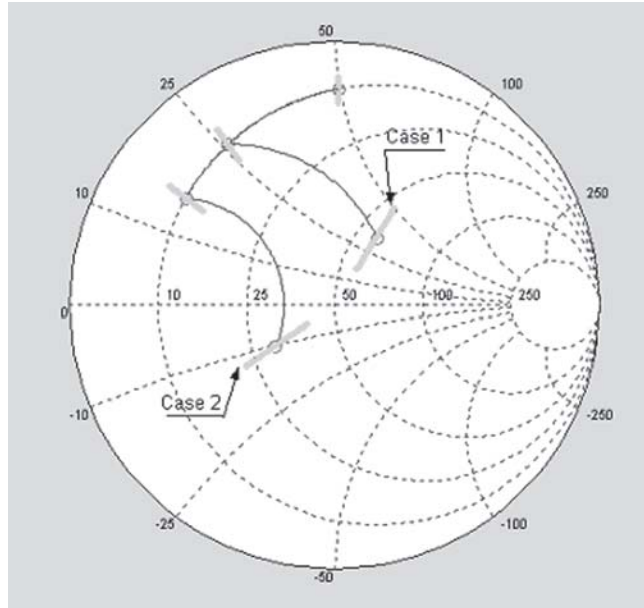

Figure 7: Impedance mismatch.

The corresponding changes in delivered power are shown in Figure 8a (case 1) and Figure 8b (case 2).

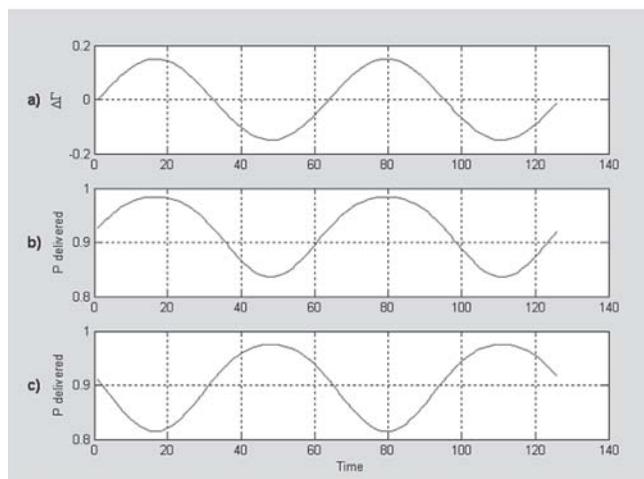

Figure 8: RF system operation (impedance mismatch).

Depending on the mismatch direction, the RF system response to the same disturbance changes by 180 degrees, which switches the feedback from negative to positive. In this case, the overall system gain completely depends upon the particular plasma impedance and match network settings and is not dependent upon any characteristic of the generator. However, the generator's loop characteristics and regulation mode can influence the magnitude of the response.

Active damping of this instability can be achieved by changing the generator's regulation mode from forward power to delivered power—this has been confirmed by numerous experiments. In delivered power regulation mode, the RF gain within the generator loop bandwidth becomes zero, which means that the generator does not respond to the impedance disturbance. As long as the generator control loop has high gain and low phase shift, other characteristics of the generator do not matter.

Fast Instabilities

In the frequency range outside the generator loop bandwidth, only the power amplifier reacts to the impedance change, which is generally valid within the instability frequency range of:

$$F_{BW} > F_{instability} > F_0/Q; \qquad \text{Equation 3}$$

where: $F_{BW} \cong 5$ kHz - generator loop bandwidth.
$F_0 \cong 60$ MHz - generator frequency.
$Q \cong 20$ quality factor of the generator output circuit

This reaction is a function of the trajectory that the impedance follows on the complex plane. In this case, the generator can be characterized by measuring its output power, with the control loop disabled, into the pattern of impedances around the operating load impedance. Based on these measurements, the contours of constant output power can be obtained. This characterization has been performed on many different generator types, and the polar plot on Figure 9 shows one of the typical responses. Solid circular contours are those of constant power. The generator reaction to the impedance change is highest when the impedance moves along a trajectory that is perpendicular to the constant power contour. The direction towards higher power is shown with the bold arrow.

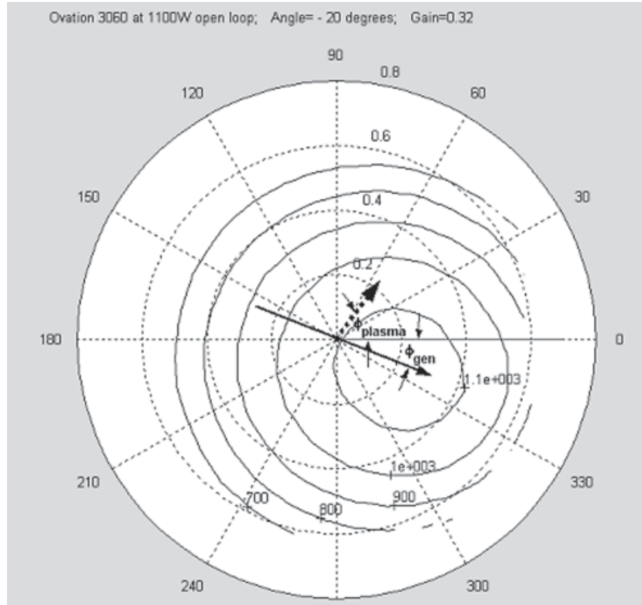

Figure 9: RF generator open loop response.

For a given steady-state impedance, the generator in this example is characterized with two values: gain, G_{RF}=0.32, and the angle of maximum gradient, φ_{gen}= -20 degrees. A similar characterization has been made on different RF amplifier topologies where their gains were found to be in the range of 0.2 - 0.9. From understanding both the gain and phase dependencies of different generator topologies, it is clear why some generators would appear to create the more stable process over others.

In order to measure plasma gain, the following sequence can be performed:

1. The automatic impedance matching system should be disabled and matched manually for a fixed output power, P.
2. An instrument for measuring the powered output impedance, Z, of the generator should be put in placed directly at the generator output terminal.
3. The generator output power, P, should be deviated at some small level, dP, to make a measurable impedance variation dZ.

Impedance variation dZ vector is shown on Figure 9 as a dashed bold arrow. After a simple calculation, the plasma gain vector can be defined as:

$$G_{plasma} = |G|*\exp(j*\varphi plasma) \quad \text{Equation 4}$$

The system loop gain is:

$$G_{sys} = |G_{RF}|*|G_{plasma}|*\cos(\theta) \quad \text{Equation 5}$$

Here, $\theta = \varphi_{gen} - \varphi_{plasma}$.

The plasma gain has been measured in many different processes for various conductor and dielectric etch tools. For the processes described in the introduction, magnitudes are in the range of 0.1 - 2.5. Usually, the plasma gain increases dramatically as both the power and/or the pressure are reduced.

The angle θ appears to be the most effective handle for improving system stability. In the systems with active impedance matching, where there is an interconnecting transmission line between the generator and match, the length of the transmission line length is easily varied, which directly affects θ while not affecting the fundamental impedance matching. For integrated systems that do not require transmission line interconnects, lumped circuits are designed in the generator to provide plasma impedance trajectory rotation, which minimizes cos(θ).

Applications

Understanding the system instability mechanisms allows some important improvements in various areas, such as RF system design, process design, and tool health monitoring.

Some RF generators have built-in features that help monitor and improve system stability, including:

- Power amplifier designs that minimize the RF gain, e.g. quadrature combiners, active DC rail control.
- Ability to measure RF load impedance.
- Control loops that allow small loop perturbations with appropriate amplitude and timing, and internal fast data acquisition to capture the response.
- If the system does not employ an external transmission line, passive lumped output circuits to minimize cos (θ).

Some RF matching networks have built-in features that can also help monitor and improve system stability, including:

- Ability to manually set capacitor positions.
- Ability to measure input impedance. Output impedance measurements are also useful in determining gain, but more cumbersome to establish the proper phase as seen at the generator output.
- Settable (non 50 ohm) impedance tune points.

During process design, the stability margin can be considered as the important parameter. It can affect the recipe as well as the proper comparison and choice of RF equipment parameters.

Real time stability margin monitoring can be used in the critical processes for chamber matching, equipment health monitoring and, in the future, for active intervention, once the appropriate algorithms will be designed and implemented.

The authors are planning to further investigate the plasma frequency response within the bandwidth of interest. The development of real time diagnostics and active instability controls are also of interest.

CONCLUSION

A system approach to RF system design provides RF solutions with improved stability, while still using high-efficiency RF amplifiers. Most of the experimental results are in agreement with the simple models presented. Some numerical disagreements are probably explained by the fact that the plasma gain in the model was considered as independent of the power disturbance frequency.

ACKOWLEDGEMENTS

The authors are indebted to D. Carter and K. Peterson for running the plasma instability experiments.

REFERENCES

1. A. Descoeudres, L. Sansonnens and Ch. Hollenstein, “Attachment-induced ionization instability in the electronegative capacitive RF discharges,” Institute of Physics Publishing, Plasma Sources Sci. Technol., Vol. 12, p. 152, 2003.

2. A.M. Marakhtanov, et al., “Stable and unstable behavior of inductively coupled electronegative discharges,” J. Vac. Sci. Technol., A21 (6), 1849, 2003.

3. M.A. Lieberman, A.J. Lichtenberg, and A.M. Marakhtanov, “Instabilities in low-pressure inductive discharges with attaching gases,” Applied Physics Letters, Vol. 75, #23, 3617, 2003.

4. B. Piejak, V.A. Godyak, and B.M. Alexandrovich, “A simple analysis of an inductive RF discharge,” Plasma Sources Sci. Technol., Vol. 1, p. 179, 2003.

5. D.L. Goodman and N.M.P. Benjamin “Active control of instabilities for plasma processing with electronegative gases,” Institute of Physics Publishing, J. Phys. D: Appl. Phys., Vol. 12, p. 2845, 2003.