Detecting and Preventing Instabilities in Plasma Processes

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ABSTRACT

RF driven plasmas commonly used in enhanced CVD deposition and etch processes are continually subject to shrinking feature size and film thickness requirements. The ongoing evolution of film architectures has driven many processes into regimes not previously explored with past technologies. Low pressure, low power processes often using electronegative gases pose unique challenges to power delivery in these increasingly demanding applications. All of these directly influence plasma impedance, a critical characteristic of any RF driven plasma. Besides the need to maintain load impedance in a range for efficient power delivery, the dynamic sensitivity of plasma impedance to other process variables can prove critical to accurate power delivery into plasma processes. Low pressure, low power, electronegative plasmas are particularly prone to stability issues, some inherent to the plasma and others resulting from dynamic interaction between the plasma impedance and the power delivery system. Today's RF power systems, in addition to becoming increasingly efficient, are also equipped with state-of-the-art measurement, regulation and control features. When properly implemented, advanced features such as variable frequency, delivered power regulation and high speed impedance measurement can be used to not only detect the presence of plasma instabilities but also to suppress and avoid them. In this paper we demonstrate the use of advanced power delivery and measurement technologies for the detection and prevention of plasma instabilities. We show characterization methods that can be used for determining process margin and effective means for power delivery optimization for ensuring process stability. For the most sensitive processes, we further demonstrate an implementation of a real time control system for plasma stabilization that detects the presence of instabilities and actively corrects them to restore stable power delivery and plasma conditions.

INTRODUCTION

As film thicknesses and feature sizes continually shrink, plasma sources and processes also must evolve in order to deliver the control and precision needed for new and next generation devices and coatings. Power delivery is becoming increasingly critical in RF driven systems as trends continue toward lower pressures, lower powers and larger electrode areas. Especially in etching and deposition processes, commonly using electronegative species, the combined effects of low pressure, low power density and electro-negativity often lead to increased risk of plasma instabilities.

Instabilities are known to occur in inductively coupled systems between stable low density (capacitive) and stable high density (inductive) modes (Figure 1). These behaviors typically occur in the 5–100 mTorr pressure range and at powers generally below about 1.5 watt/cm^2 (electrode area). Within this region oscillation in particle density, optical emission and coil voltage have been observed [1,2]. Instabilities can also occur in capacitively coupled plasmas where electron attachment to electronegative species has been found to cause similar oscillatory behavior [3].

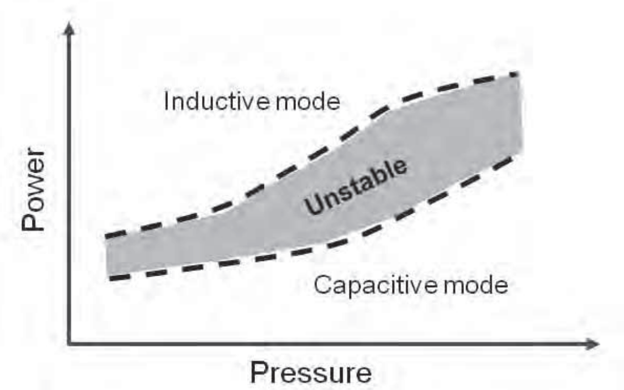

Figure 1: For inductively driven plasmas an unstable region can exist between the high power inductively coupled plasma mode and the low power capacitively coupled plasma mode.

Depending on many factors, the nature of unstable oscillations can vary dramatically. Severe instabilities can cause noticeable flicker in plasma intensity but less acute cases can go unnoticed. Oscillations can drive sudden and rapid changes in plasma impedance with frequencies ranging from a few hundred hertz to well over 100 kHz. Figure 2 gives two examples of plasma instabilities captured in forward and reflected power and Figure 3 examples of instability impedance trajectories. It is noted that low frequency instabilities often result in dramatic swings in impedance with large hysteresis (Figure 3a), while high frequency trajectories are often smaller in amplitude and tend to be monotonic in nature (Figure 3b).

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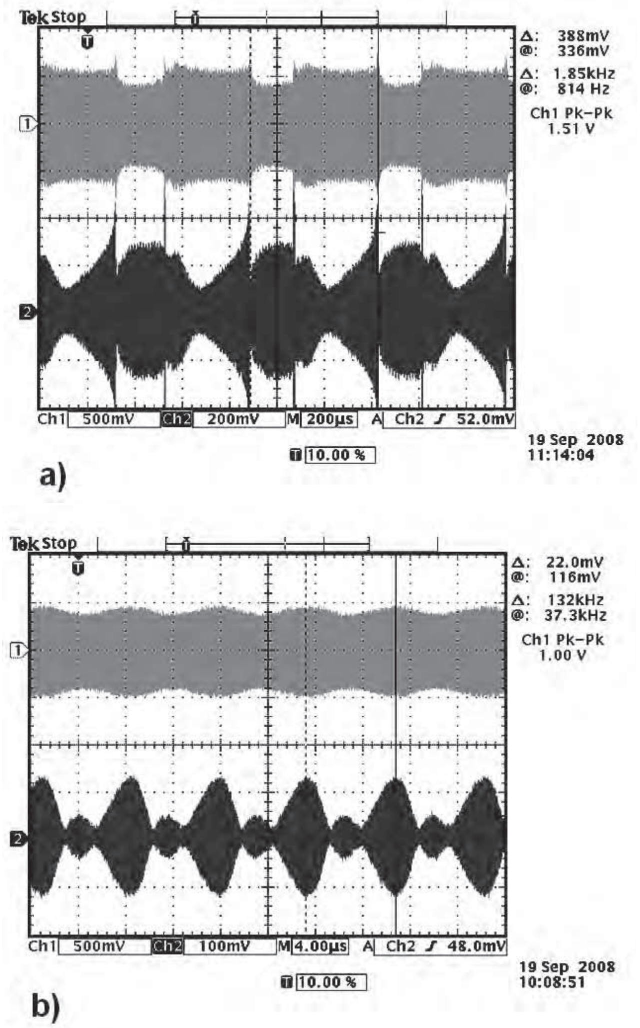

Figure 2: Forward (Ch1) and reflected (Ch2) power captured in presence of plasma instability a) oscillations frequency ~ 1.85 kHz and b) oscillation frequency ~ 132 kHz.

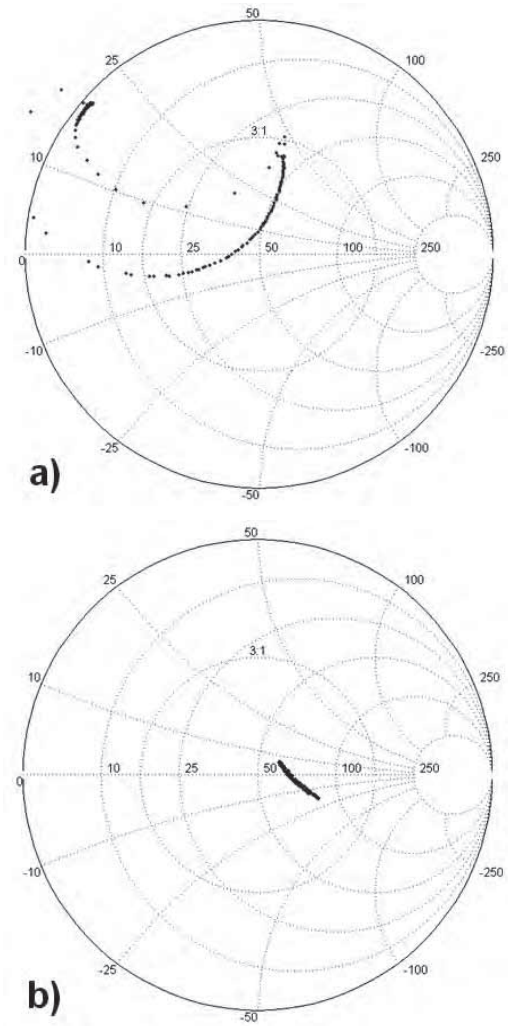

Figure 3: Impedance trajectories of a) a low frequency instability and b) a high frequency instability.

Power monitoring through a directional coupler is an effective way to watch for instabilities but such a method usually requires external instrumentation not always available. Since instabilities may not be visually observed, detection can be difficult so addressing the issue first requires a reliable measurement and then a proven method for correction.

Power delivery to a plasma plays an important role since dynamic load sensitivity can influence an amplifier's susceptibility to instabilities. Many modern power topologies offer numerous advantages including improved efficiency, compact size and low cost; but one disadvantage can be increased risk of plasma instabilities. Especially for high efficiency, switch mode amplifiers, generator-plasma interaction can both promote the formation and increase the severity of plasma instabilities.

Brouk et al. [4] previously examined the generator-plasma interaction, illustrating in electrical terms how plasma impedance reacts to changes in applied power and in turn how amplifier output responds to changes in load impedance. In this article these basic interactions are reviewed to illustrate how this understanding relates to traditional methods for dealing with stability. Further it is shown how newly available technologies, namely high speed impedance measurement and variable frequency tuning, can detect and correct instabilities and how these new capabilities allow for the advent of active stability control in low pressure, low power, electronegative plasmas.

GENERATOR-PLASMA INTERACTION

Figure 4 shows typical power output profiles (deviation from set point) of a modern switch-mode power amplifier operating at a fixed output into varying load impedances. Data in Figure 4a was collected under active power regulation and shows the output profile centered at 50 ohms load impedance. Data in Figure 4b was collected with no active power regulation (open-loop) showing the center of the profile well removed from 50 ohms. The centered profile in Figure 4a is easily achieved in normal plasma conditions, where typically, slow impedance changes are accounted for by the generator's control loop. Figure 4b is more indicative of the instantaneous output from the generator when experiencing rapid changes in impedance (such as those associated with instabilities) that are outside the bandwidth of the control loop.

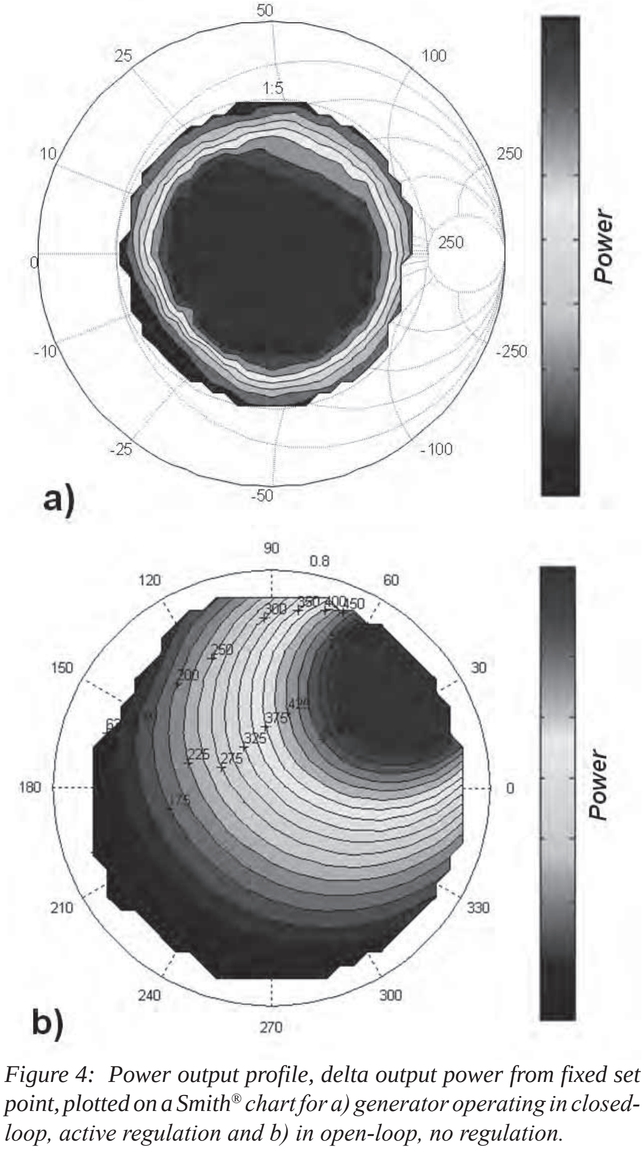

Figure 4: Power output profile, delta output power from fixed set point, plotted on a Smith® chart for a) generator operating in closed-loop, active regulation and b) in open-loop, no regulation.

The dynamic response of a generator's output (generator gain) indicates its inherent sensitivity to impedance perturbations, including plasma instabilities, and can be represented as a vector in the complex impedance plane. Important for the interaction with plasma, the generator gain or G_{Gen} has both direction and magnitude components (see Figure 5a). In turn, the sensitivity of the plasma's impedance to changes in applied power can be similarly represented as the plasma gain (G_{plasma}) also having a magnitude and direction in impedance space (Figure 5b).

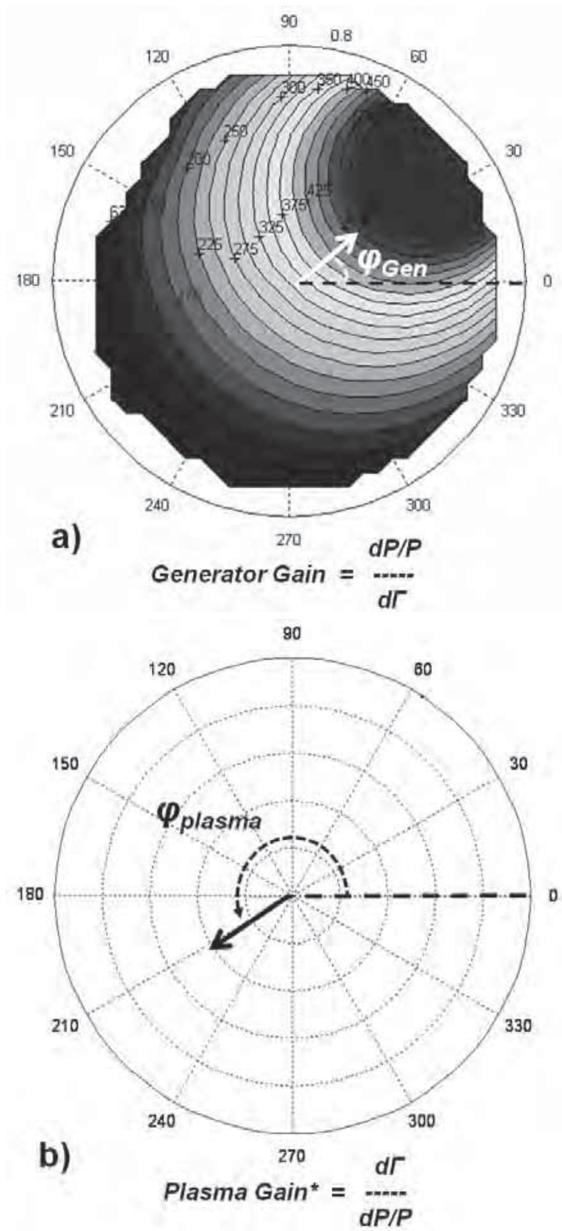

Figure 5: a) Generator gain, G_{Gen} and b) Plasma gain G_{plasma} (as translated through the match and transmission cable).*

Critical to the affects of the generator-plasma interaction are the magnitudes of the gain factors and the vector angles φ. The orientation of φ_{Plasma} with respect to φ_{Gen} strongly influences the overall system gain, G_{Sys}:

$$G_{Sys} = |G_{Gen}| * |G_{Plasma}| * \cos\theta \quad (1)$$

where θ is the difference between angles φ_{Plasma} and φ_{Gen}. For a given generator G_{Gen} is essentially constant. G_{Plasma} however is influenced by process conditions and external componentry as will be shown below. Important for stability, as discussed by Brouk [5], when G_{sys} exceeds unity, the system is at risk of becoming unstable.

To properly account for all contributions, the trajectory angle of the plasma impedance should be represented as φ_{Load} (and G_{Plasma} as G_{Load}) because when referenced from the generator, φ_{Plasma} is translated through the match network and transmission cable, both typical components in the RF delivery path. Each element in the delivery path contributes to the angle φ_{Load} and in turn the resulting θ (Figure 6). This point highlights the impact transmission cable length has on θ and its resulting influence on system gain and ultimately plasma stability.

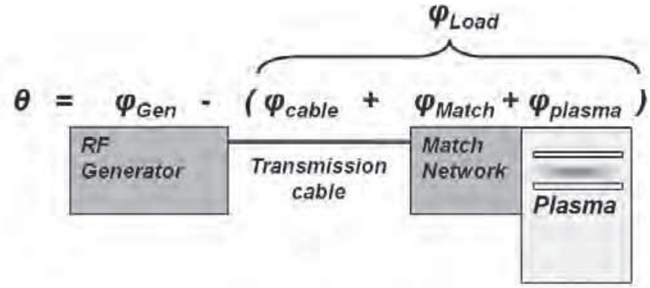

Figure 6: Contributors to angle θ.

Adjusting transmission line length is a traditional means for avoiding plasma instabilities. In practical terms, cable length affects transmission delay which translates to rotation of φ_{Load}. This has a direct impact on the $\cos\theta$ term in Equation 1 and therefore is a proven means for improving plasma stability. Proper adjustment of cable length can favorably affect θ resulting in decreased system gain. Unfortunately, operating conditions can affect both magnitude and angle of G_{Load} so an ideal cable length for one process may not be best for another set of conditions. While cable optimization can offer improvement, as processes and systems become increasingly complex, the technique becomes less and less effective for ensuring continuous system stability.

Rotation of load trajectory (φ_{Load}) through cable length can also be a valuable characterization technique offering further insight into the generator-plasma interaction. RF cable length can be used to rotate φ_{Load} in a controlled manner allowing for evaluation of stability margin. A practical method for accomplishing this is to incrementally add sections of transmission cable into the delivery path while measuring minimum stable power for each incremental length (Figure 7). Once a total addition equivalent to 360° rotation in φ_{Load} (or approximately 25 ft of standard cable at 13.56 MHz) is inserted, the stability profile is complete. This picture then repeats itself as additional cable lengths are inserted.

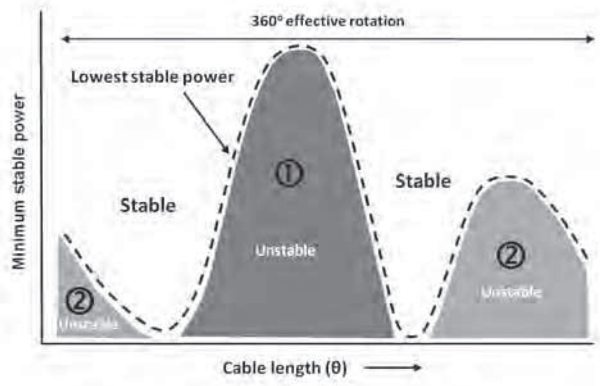

Figure 7: Typical cable length stability profile for an inductively coupled, low pressure, electronegative plasma.

A key feature in the cable length stability profile is the presence of stable and unstable regions within the 360 degree φ_{Load} rotation. Some systems show a single unstable region but it is not uncommon for two stable and two unstable regions to appear. The two stable regions occur when the term $\cos\theta$ in Equation 1 approaches zero at θ values of 90° and 270°. The two unstable regions occur as a result of system feedback experienced on either side of these preferred θ angles.

From Figure 7, stable, low power plasma performance can be achieved by choosing a transmission cable length within the stable regions. As mentioned above, this approach can be effective for addressing stability for a narrow set of conditions, but it is known that for processes with a multiplicity of chemistries and operating conditions, finding a single optimal cable length can become problematic.

RF frequency directly affects the electrical equivalent of cable length. In identifying a practical means for establishing and maintaining stability, frequency represents a much more convenient method compared to changes to physical cable length. With a fixed transmission length, RF frequency can be used to rotate φ_{Load} having a similar effect on plasma stability to that of the physical cable but accomplished using a parameter easily implemented into a real time feedback and control system.

FREQUENCY BASED PLASMA STABILIZATION

Figure 8 plots minimum stable power through a partial φ_{Load} rotation in a low pressure, electronegative, inductive discharge. The effects of both cable length (at fixed frequency) and frequency (at fixed length) are shown. Across the tested range (limited by the frequency range of the generator) there is very close agreement between the effects of frequency and those for physical cable length. The close agreement in the stability trends confirms the use of frequency as a “knob” for controlling stability of the plasma through electrical rotation of the angle φ_{Load}.

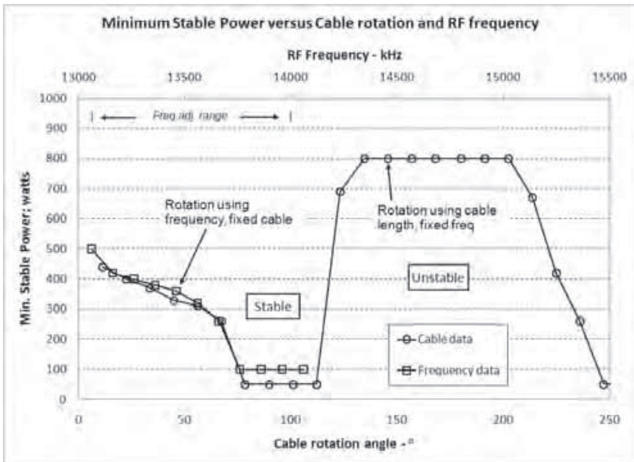

Figure 8: Minimum stable power at varying cable length and RF frequency. Comparable trends confirm cable length and RF frequency are interchangeable.

Frequency tuning offers a viable means for stability control but must be accompanied with accurate measurement for detection and feedback to a control loop. As mentioned above, sensing instabilities can be a challenge. Oscillation frequencies can vary from a few 100 Hz to well over a 100 kHz. An external directional coupler feeding an oscilloscope is a proven detection method (see Figure 2) but is not practical for shop-floor implementation. A preferred approach would eliminate external components and still provide adequate sensitivity and dynamic resolution. Direct measurements taken at the output of the generator is most convenient but proper selection and processing of available data is necessary to make good use of the information available.

Since impedance varies rapidly during periods of instability, monitoring short duration changes in reflection coefficient (reflected power/forward power, or Γ) is an effective way to assess stability. Standard deviation (σ_Γ) can be calculated periodically from a sampling of gamma. The magnitude of σ_Γ can then be used to detect the presence of instability and quantify its severity when present. Process and control system requirements dictate the necessary sampling rate. The automated detection and correction approach discussed below required very fast Γ sampling to be effective. In this case forward and reflected power are sampled approximately every microsecond and (σ_Γ) is updated every few milliseconds.

An example of automated instability detection is shown in Figure 9. As illustrated above, for an inductive, electronegative discharge a minimum stable power exists for each cable length. Above this power - approximately 700 watts at the highlighted cable length (Figure 9a) - σ_Γ is low, near zero (Figure 9b). Below this threshold, σ_Γ increases rapidly indicating the presence of instability. σ_Γ remains high until the inductive mode of the plasma is lost (due to inadequate power coupling) and the discharge transitions to a low density capacitive state. At the lower powers (below 200 watts) the plasma is once again stable.

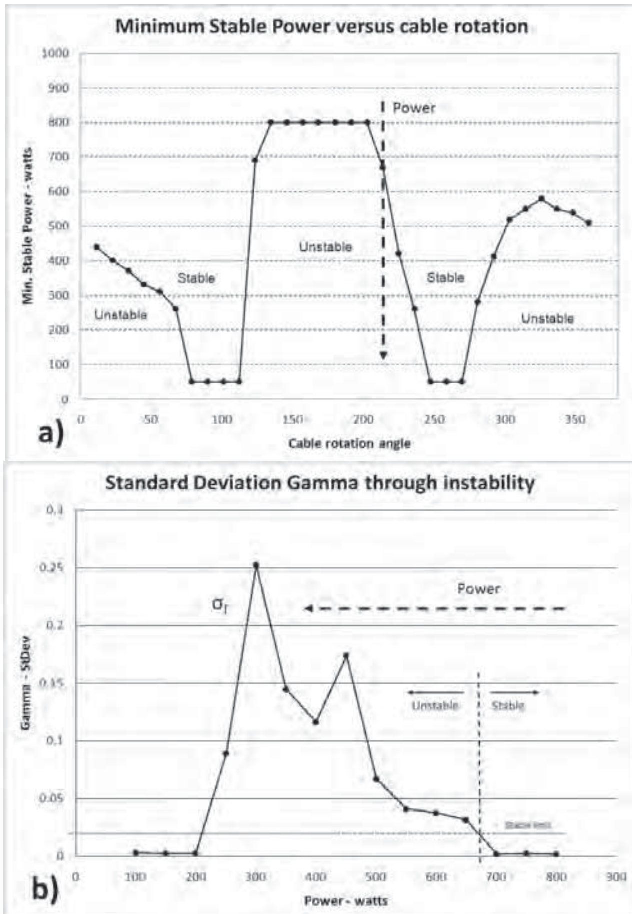

Figure 9: Instability for a given cable length measured using σΓ. σΓ is low, near zero above the instability power threshold and increases rapidly as power is decreased below the stable threshold.

Using these rapid σ_Γ measurements, a proprietary control loop was defined to maintain stable plasma operation using frequency adjustment. When instabilities are detected, based on σ_Γ, the control system makes appropriate changes to frequency, affecting the electrical cable length, rotating the load impedance trajectory in order to achieve a more favorable θ and regain stability. The technique was applied to an inductive, electronegative discharge operating at 13.56 MHz (at a fixed cable length similar to that shown in Figure 9). A directional coupler at the output of the generator captured the power oscillations when the unstable threshold was crossed (Figure 10a). Once engaged the control loop adjusts frequency of the RF output to regain stability. Figure 10b shows the resulting power traces after loop engagement, indicating a recovery to stable operation. In this case the criterion for stability was $\sigma_\Gamma < 0.02$. Once σ_Γ exceeded 0.02, frequency tuning was initiated. For this process the instability was corrected by a 180 kHz increase applied to the RF frequency.

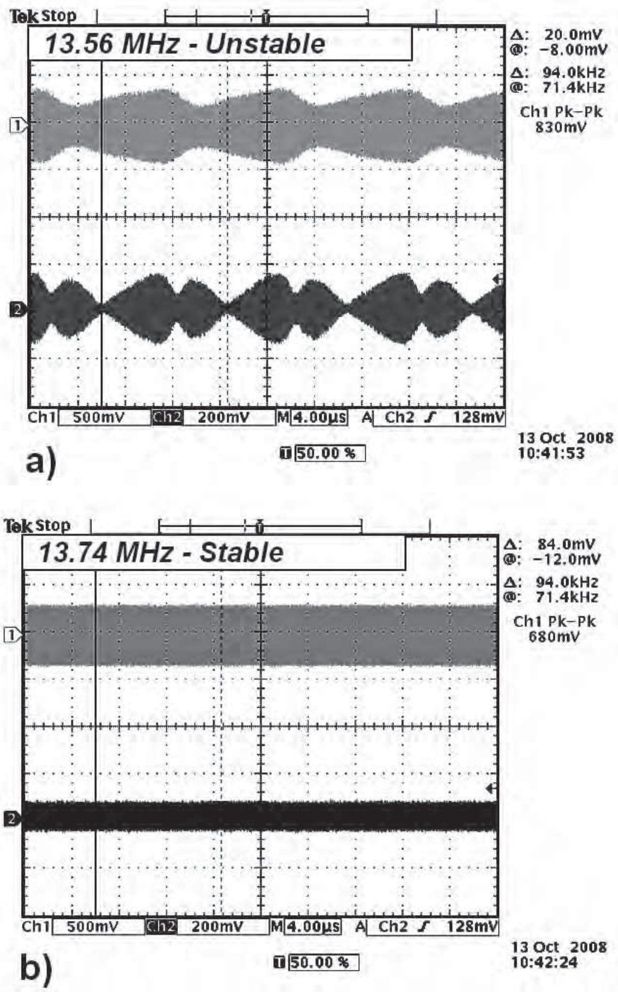

Figure 10: Oscilloscope traces of forward (Ch1) and reflected power (Ch2) in an unstable inductive discharge at 13.56 MHz (a). Stable discharge restored after frequency adjusted to 13.74 MHz (b).

An important consideration with this approach is the frequency range of the generator. A finite bandwidth in frequency establishes the limits to which θ can be affected. In the example above, the RF generator had a frequency range of approximately ±5% around 13.56 MHz. Using RG393 co-axial transmission cable, this range provides a maximum of approximately 140° of φ_{Load} rotation. Note, in Figure 7 the frequency range tested was from 13.06 – 14.06 MHz, providing just over 100° of effective rotation. This finite range in frequency adjustment defines the range of stability control available from this approach. As a result some optimization in cable length is still necessary to ensure the desired stable regions are accessible within the available range of frequency rotation.

Changes to RF frequency also impact impedance matching which can result in increased reflected power after frequency based stabilization. Some amount of reflection is not detrimental to a process if the power supply is configured to compensate and maintain delivered power (and has necessary headroom). Retuning may be necessary if reflected limits are reached or if zero reflected power is required. This can be a complication since, referring to Figure 6, retuning can also impact φ_{Load} as seen by the generator. To avoid issues the control loops for tuning and stabilization in the above example were synchronized to avoid conflicts. By using this approach, stability can be achieved in most cases while also matching to minimum reflected power.

CONCLUSIONS

Plasma instabilities can commonly occur especially in inductively driven low power, low pressure electronegative discharges. In modern systems utilizing switch-mode high efficiency RF power supplies, the interaction between plasma impedance and amplifier output can reinforce or intensify fluctuations in plasma properties. The interaction between plasma and delivery system has been studied leading to an understanding of these behaviors and a definitive explanation of traditional measures as well as new methods to avoid unstable plasma conditions.

As plasma processes drive toward more demanding operating regimes, the need for improved stability control has evolved. Understanding the sensitivity of amplifier output to impedance trajectory has led to the identification of RF frequency as a lever for maintaining stable operation. RF frequency behaves as the equivalent to physical cable length providing rotation of the critical φ_{Load} angle of the impedance trajectory. Using frequency as a control parameter, a control system for managing plasma stability can be devised.

Effective control requires reliable measurement able to resolve oscillations in the 100s kHz range. A measurement system based on σ_Γ calculation was demonstrated capable of sensing modulation associated with plasma instabilities providing both detection and magnitude assessment. Combining high speed measurement with a proprietary control loop, once detected, instabilities can be eliminated through appropriate adjustment in RF frequency.

Frequency bandwidth of the RF generator and impedance matching requirements are practical considerations for implementation. A finite frequency band defines the functional range for stability correction by determining maximum φ_{Load} rotation. Retuning can affect stability correction since reactive elements within the match also affect φ_{Load}. Proper synchronization between multiple control loops is necessary to avoid conflicts and allow for stabilization while also tuning to low reflected power.

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REFERENCES

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

2. 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.

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. V. Brouk and R. Heckman, Stabilizing RF Generator and Plasma Interactions, *47th Annual Technical Conference Proceedings of the Society of Vacuum Coaters*, pp 49-54, 2004.

5. V. Brouk and R. Heckman, Stabilizing Plasma and Generator Interactions, U.S. Patent 7157857, 2007.