Numerous challenges face designers and users of today’s RF plasma chambers. As feature sizes continue to scale and film stacks increase in complexity, the demands being placed on contemporary systems continue to grow. Adding to the challenge is the ever-present need to improve productivity, reduce cycle times, and today more than ever, to optimize multiple, highly dissimilar processes within a single chamber. To meet these requirements, systems today need to be not only accurate and highly repeatable under steady state conditions, but also maintain their accuracy and repeatability during transients and fast-changing processes. Systems need to be extremely flexible and especially agile in adapting to a broad range of process conditions and fast-changing process chemistries.

These wide-ranging demands place some of the greatest burden on the RF power-delivery and control systems driving the plasma formation in processing chambers. To meet these challenges, a power-delivery system needs to be both accurate and repeatable, and also capable of delivering controlled power into highly diverse and often dynamically changing plasma loads.

Process Technology Challenges for Power Delivery

One of the byproducts of shrinking features is increasingly complex film stacks and masking structures. Especially at critical levels, the simple deposit, pattern, and then etch process flows are no longer adequate. As an example, today’s etch processes often must account for anti-reflective coatings, hard masks, cap layers, and stop layers in the process recipe, while accurately etching the primary layer, which may comprise multiple compositions and doping profiles. In some cases, eight or more layers are involved in the patterning and etching of a single critical device level [1]. Adding to the challenge is the dissimilar chemistry required to etch the various layers and an increasing need to accomplish such complex stack patterning with the fewest number of individual wafer cycles [2].

It is now common for plasma processing chambers to be equipped with multiple powered electrodes, often operating at different frequencies. The manipulation of plasma characteristics such as density, ion energy, ion current, and neutral density is largely related to the way in which power is coupled to the plasma, making the power delivery and control to these processes increasingly critical. Another emerging method for managing plasma characteristics is the use of pulse-modulated power. Pulsing offers some intriguing possibilities for modifying plasma behaviors, but it presents some significant challenges for the power-delivery and control systems, such as maintaining pulsed power regulation under changing load impedance conditions. These issues make active impedance matching using a traditional matching network virtually impossible.

The trend toward higher aspect ratio structures presents additional complexities to power delivery. At the extreme are some of the processes used for DT (deep trench) etching, HARC (high aspect ratio contacts), and TSV (through silicon via) interconnect formation. High aspect ratio structures found in IC fabrication are becoming similar to what is seen in MEMS processing and often require repeated in-situ etch/deposition sequences, creating added power control and delivery challenges during fast-transitioning process chemistry cycles.
Finally, the economics of equipment utilization drives the requirement to integrate more and more process steps into fewer and fewer chambers. The need for broad operating ranges and flexible recipe control demands highly adaptable and configurable power-delivery systems across a wide range of plasma conditions. Decreasing process overhead is also critical to capital utilization [3]. In addition to flexibility, high-speed regulation and tuning during multi-step processes can be keys to increasing tool utilization by minimizing the overhead associated with intra-step stabilization.

Advanced Power-Delivery Systems Meet the Challenge

Power delivery in RF plasma chambers is accomplished through the effective integration of two critical subsystems: 1) An RF power generator, responsible for the generation and the accurate control of the RF power delivered to the plasma and 2) an impedance matching network to assist in the transformation of the different plasma loads into an impedance range where the generator is able to deliver the required power. These two subsystems must work together to provide accurate and repeatable power into the plasma while maintaining the widest possible operating range.

To meet the challenges of today’s processes, an RF power-delivery system must provide the following capabilities:

• Extremely accurate power measurement and delivery for precise power regulation into all load conditions
• Operation across wide impedance ranges to provide process flexibility and performance on dissimilar process chemistries
• Sophisticated plasma-impedance metrology for accurate tracking of and compensation for impedance changes experienced in multi-step recipes and cyclical processes
• Highly agile tuning to ensure absolute power delivery into increasingly complex processes featuring fast transients or multiple process cycles
• Fast ignition and settling to minimize overhead and maximize ignition and tuning consistency
• Advanced features including pulse modulation, pulse synchronization, and phase matching for enhanced performance on next-generation structures

Until recently, these features were not available in any single RF power system. The new Advanced Energy® Paramount™ RF Power-Delivery System mated with a Navigator® Digital Matching Network is the first-ever commercial offering delivering all of these capabilities in a single solution. The integration of the Navigator Digital Matching Network, with its accurate, broad-range tuning capability, and the Paramount Power-Delivery System, featuring extremely accurate output regulation along with high-speed frequency agile tuning and pulse modulation, offers unmatched performance for meeting the demands of next-generation process architectures.

The performance features and capabilities of the integrated Paramount/Navigator system were demonstrated through a battery of tests performed into linear and plasma loads. Linear load testing was performed using fixed loads at times interfaced to counter-match elements to produce non-50 Ω impedance conditions. Plasma testing was performed in a semiconductor-class plasma reactor equipped with both ICP and CCP electrodes.

The power-accuracy capability of the Paramount Power-Delivery System into 50 Ω and non-50 Ω loads is given in Table 1. Delivered power accuracy is extremely precise: 0.25 W at low power levels. Beyond the ability to accurately regulate power into static, non-50 Ω conditions, these capabilities allow accurate power regulation through many process and impedance transients, allowing for accurate power control and delivery even during process transitions.

Table 1. Power accuracy of the Paramount™ Power-Delivery System

<table>
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<tr>
<th>Into 50 Ω</th>
<th>±0.25 W or 1% of set point, whichever is greater</th>
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<tbody>
<tr>
<td>Into 3:1 VSWR</td>
<td>±2 W or 2% of set point, whichever is greater</td>
</tr>
<tr>
<td>Regulation</td>
<td>5 to 3,000 W</td>
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Transients are increasingly common in multi-step plasma process recipes as operating conditions are continually tailored for the film stacks being deposited or etched. Through these transients, a power-delivery system must respond to load impedance changes in order to maintain a stable process. A simple change in gas-flow mixture can result in a significant change in the impedance experienced by a power supply. Figure 1 shows load impedance changes resulting when a 1:1 mix of gases A and B is transitioned to all gas A and then to all gas B. To illustrate this behavior dynamically, the plasma load was initially tuned to 50 \( \Omega \) at ignition before the matching network tuning system was switched off. The gas flows were then cycled and the impact to impedance seen by the RF generator was measured utilizing the generator’s measurement system and plotted on a Smith\(^\circ\) chart (Figure 1a). The temporal change in VSWR is shown in Figure 1b.

In Figure 1, power delivery to the plasma is maintained using load power regulation. This mode of operation represents the fastest method for maintaining power delivery during changes in plasma impedance. However, load power regulation may be limited by the power required or the impedance change brought on by the process. In this case, compensation must be made in order to minimize reflected power. Compensation for such changes in impedance is traditionally handled by a variable matching network. Figure 2 shows an impedance data log captured when the Navigator match network actively re-tunes through the process transitions to maintain a near-50 \( \Omega \) match at all times. Here, VSWR remains below 1.5:1, allowing efficient power delivery to the process through the changes in gas flows.

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**Figure 1.** Gas-flow induced impedance changes experienced by the RF power supply in an ICP plasma under fixed match conditions
A variable matching network offers a highly flexible means for minimizing reflected power, as shown in Figure 2. But variable matching networks are relatively slow due to the need to mechanically adjust capacitor values during the tuning process. For large impedance swings, the Navigator match is extremely effective at tuning to low reflected power. When process transitions become rapid or highly cyclical, a variable match network may have difficulty maintaining adequate match due to the slow response of mechanically driven tuning capacitors. In cases where fast matching into wide impedance swings is necessary, alternative methods are required. The sweep frequency tuning feature in the Paramount Power-Delivery System offers extremely fast impedance matching to compensate for rapid process transients and cycles. Figure 3 shows the Smith Chart (Figure 3a) impedance values and the power-delivery data log (Figure 3b) during sweep frequency tuning in the two gas process cycle described above.
Fast frequency tuning can significantly extend the usable range for load power regulation, resulting in a broad, yet highly agile operating region. For very large impedance changes, however, a variable matching network will still be required. (See Table 2.) Proper implementation of each element provides the highest agility with the broadest operating range available.

Sweep frequency tuning is enabled by the integration of an accurate impedance measurement system into the control systems of a frequency agile RF power supply. The Paramount system’s impedance measurement is exceedingly accurate (Figure 4) across a broad range of loads. The extremely fast and ultra-accurate impedance measurement enables the optimum tuning frequency to be quickly realized. When extremely fast tuning is necessary for near-instantaneous ignition, where process changes become highly cyclical, or when very rapid plasma chemistry cycling is required, sweep frequency tuning can be an enabling technology.

Table 2. Comparison of power delivery/impedance matching options

<table>
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<tr>
<th>Option</th>
<th>Advantage</th>
<th>Disadvantage</th>
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<tbody>
<tr>
<td>Delivered power regulation</td>
<td>Extremely fast, accurate power delivery to into 50 Ω and non-50 Ω loads</td>
<td>Limited range depending on required power or changes in load impedance</td>
</tr>
<tr>
<td>Variable match with auto-tune</td>
<td>Widest impedance matching range available, adjustable pre-sets for minimizing time to achieve match</td>
<td>Relatively slow mechanical components in match subject to wear in highly cyclical processes</td>
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<tr>
<td>Frequency agile tuning</td>
<td>Very fast, broader impedance range for load regulation</td>
<td>Operating range still smaller than variable match</td>
</tr>
<tr>
<td>Load power regulation with frequency agile tuning integrated with variable match</td>
<td>Broadest operating range, fastest performance available</td>
<td>None</td>
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The speed of the Paramount system's sweep frequency tuning algorithm is best illustrated on extremely fast impedance cycles. Vacuum pressure changes and gas-flow steps are common sources of impedance swings. But due to relatively slow diffusion rates, these transitions can be slow compared to the speed of the frequency tuning algorithm built into the Paramount system. To better illustrate the speed of the tuning capability, much faster impedance changes caused by power cycling were used. An example of a fast impedance step and the frequency tuning response of the Paramount system is given in Figure 5.
By stepping power up and down under otherwise fixed process conditions, a very fast impedance change occurs. In the oscilloscope trace in Figure 5, the change in power and response from plasma occurs over a period of approximately 800 µsec. In the scope trace, the step in power is indicated by a rise in the forward power. An increase in the reverse power is also indicated due to a change in impedance of the plasma. Once the re-tune begins, the frequency tuning loop is shown to reduce the reflected power to the user-defined limit in approximately 232 µsec. Similar tests performed on a variable matching network required several hundred milliseconds to accomplish a similar re-tune.

Overhead time required for tuning at ignition can be reduced through the use of capacitor pre-sets on the Navigator matching network. Figure 6a shows an ignition impedance trajectory typical when no pre-sets are defined for the capacitor positions. Figure 6b shows the improvement when properly chosen pre-sets provide faster ignition. The time to ignite and reach proper tune in this example was reduced from approximately 2.7 seconds to just over one second for the pre-sets case. If further reduction is required, the Paramount frequency tuning capability can be used to significantly reduce the ignition time. Ignition and tune can be accomplished in less than 50 milliseconds when using the fast frequency sweep capabilities of the Paramount Power-Delivery System (Figure 6c).
Fast re-tuning capability may be most valuable when rapid and frequent process cycles are required. When accurate, uninterrupted power delivery is needed during rapidly cycling processes (~1 sec), traditional matching using a variable match network may be inadequate to maintain effective match and power regulation. Figure 7 shows impedance results from a process cycled between dissimilar gas flows every two seconds (Figure 7a). Figure 7b shows the impedance excursions experienced when a variable match is used for re-tuning through the transitions. Although match is achieved for each cycle, the delays in the mechanical response of the match network cause variable levels of mismatch and reflected power to be recorded during each transition. Figure 7c shows the significant reduction in impedance excursions resulting from the more agile frequency-based tuning capability in the Paramount Power-Delivery System. The response speed of the Paramount sweep algorithm is fast enough to accurately track the impedance during the transition from gas A to gas B, preventing large deviations in the tune or in reflected power experienced by the power supply.
Figure 7a. Gas-flow cycles inducing repeated impedance changes experienced by power-delivery system.

Figure 7b, c. Impedance changes resulting from rapidly cycling gas-flow transitions in an ICP plasma. Significant impedance excursions (b) are experienced when using a variable match network; Paramount™ frequency agile tuning (c) results in far less impedance variability.

Figure 7d, e. Data logs of forward and reflected power for (d) fixed frequency and variable match network tuning and (e) frequency agile tuning with a fixed match network position. Paramount™ frequency agile tuning provides faster ignition and decreased incidence and magnitude of excursions compared to the variable match tuning.

Re-Tunes After Process Steps

Ignition Tune Trajectory Too Fast for Logging (< 10 msec)

Re-Tunes After Process Steps

Ignition Tune Trajectory

Delivered Power

Power

Frequency

Frequency

Reflected Power

Delivered Power

Time

Time
The need to tailor plasma behaviors beyond what is available from power, pressure, and flow alone has led to increasing interest in pulse-modulated RF power. Pulsing allows for high peak power to be delivered in short pulses to drive ionization and dissociation of reactive species but at lower time-averaged power. Pulsing can create some undesirable issues for a variable match network, however, as the tuning system detects impedance swings between pulses and attempts to compensate. Unstable behavior results because the mechanically driven variable match is far too slow to effectively re-tune the plasma impedance while pulsing.

The high-speed frequency tuning capability and fast impedance measurement of the Paramount Power-Delivery System addresses this issue, allowing for dynamic tuning, real time, even while RF power is pulsed. Figure 8 shows an oscilloscope trace of frequency tuned pulsing during plasma ignition.

The high-speed frequency tuning capability and fast impedance measurement of the Paramount Power-Delivery System allow for dynamic tuning, real time, even while RF power is pulsed.

When power is initially turned on, high reflected power is registered on the oscilloscope trace. During the second 100 Hz pulse, the frequency tuning algorithm is initiated and reflected power falls. Approximately half way through the second pulse (< 1 millisecond after being initiated), reflected power has been reduced to the user-defined set point and the tuning process is complete. In this example, the starting frequency was 13.56 MHz and tuning was complete at 13.81 MHz, approximately 15 milliseconds after power was applied.
Combining load power regulation, sweep frequency tuning, and a configurable matching network platform offers the most flexible and capable power-delivery solution to the system designer and the process engineer.

Discussion

Complex film stacks and exacting standards for plasma-based thin-film processing places unprecedented demands on today’s RF power-delivery products. Requirements to maintain tight process control on multi-step processes featuring wide-ranging plasma impedances, highly varying chemistries, in-situ gas cycling, and possibly RF power pulsing, demand a highly sophisticated and capable power-delivery technology. A flexible and highly featured configuration is the key to optimized performance. Where wide impedance swings are expected, a variable match is required. But when speed and agility are essential, additional tuning capabilities are necessary. In this case, the mechanical match can be used as a pre-settable fixed match, and a complimentary yet faster matching and regulating method employed.

To achieve consistent power coupling through fast transitions, load regulated power into a non-50 $\Omega$ match provides the fastest available option for delivering power. However, depending on the power required for the process, this approach may be limited for processes requiring high power or experiencing large changes in impedance. Sweep frequency tuning is a complementary technology extending the range of load regulated power. Properly implemented, fast tuning loops can rival power regulation for speed and agility in delivering power to fast-transitioning processes even when large impedance changes are present.

Combining load power regulation, sweep frequency tuning, and a configurable matching network platform offers the most flexible and capable power-delivery solution to the system designer and the process engineer. Such an integrated solution offers accurate RF tuning across a broad impedance range, while also providing the agility, performance, and reliability needed to handle the most demanding dynamic processes.

Sweep frequency tuning has the added benefit of allowing RF matching during pulsed operation. Pulse modulation presents significant issues to traditional matching networks and RF power supplies, but the accurate power and impedance measurement and the fast frequency response built into the Paramount system makes possible the ability to both regulate power and actively tune across a wide range of pulsing frequencies and duty cycles.

Conclusion

The ability to combine the broad tuning range and configurability available in the Navigator Digital Matching Network with the high accuracy at high VSWR and the fast frequency tuning algorithms in the Paramount RF Power-Delivery System offers unique capabilities to meet the most demanding next-generation processes. The complimentary capabilities of the combined products offer unprecedented flexibility and accuracy, opening up new territory for plasma process precision and performance.
**References**

