The Impact of Remote Plasma Chamber Cleaning Systems on Cost of Ownership for Semiconductor Manufacturers

Created by

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Abstract

Cost of Ownership (CoO) is a key parameter in the selection and use of semiconductor manufacturing systems. Although remote plasma sources (RPS) have been a part of the industry for many years, customers do not regularly define which RPS system is specified in the CVD systems purchased from major OEMs. This paper reviews the key considerations in the cost of ownership for remote plasma sources used in CVD chamber clean and how those choices can greatly impact a customer's CoO.

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Introduction

Remote plasma sources used in the cleaning of CVD, PECVD and PEALD chambers are standard practice in today's semiconductor industry. The purpose of these clean modules is to eliminate (or lengthen the time between) major cleans in a chamber, maintain consistent process conditions for better CVD performance, and control or reduce particles in a chamber. Although CoO models are usually run for the main CVD system prior to choosing a supplier, the remote plasma source used for chamber cleaning is not typically reviewed for the CoO model. This paper goes into the detail of a CoO model for remote plasma sources in this application and suggests ways to decrease the CoO for the chamber clean activity, thereby increasing overall system productivity and yield.

Part 1: Cost of Ownership Models

In a cost of ownership model, there are some very basic parameters which can be tracked to ensure an accurate look at the cost of any system. The following parameters are critical in assessing cost of ownership in these models:

- Capital Cost – Amount paid for the unit upfront
- Uptime – Amount of productive time the module provides
- MTBF – Mean time between failures
- MTTR – Mean time to repair
- MTTI –Mean time to interrupt
- Particles – Particles generated by the module that cause repair or intervention
- Product Yield – Impact of the module on product yield
- Repair Costs – Average cost to repair a module
- Repair Time – Average time to repair a module
- Interrupt Clear Time – Assumed to be two hours for most cases

In addition to these parameters, a chamber clean source CoO model also needs to incorporate aspects specific to the fact that a remote plasma source has its own chamber for generating a plasma and thus must assess the:

- Repair costs specific to chamber replacement
- Chamber lifetime

Part 2: Key Factors in the CoO Model for Remote Plasma Sources

What are the key factors in chamber clean modules that affect CoO, and are they strong or weak factors?

As any process engineer or yield manager will tell you, particles are the most important factor for semiconductor processing, especially in processes in the sub-30 nm range. In fact, one could

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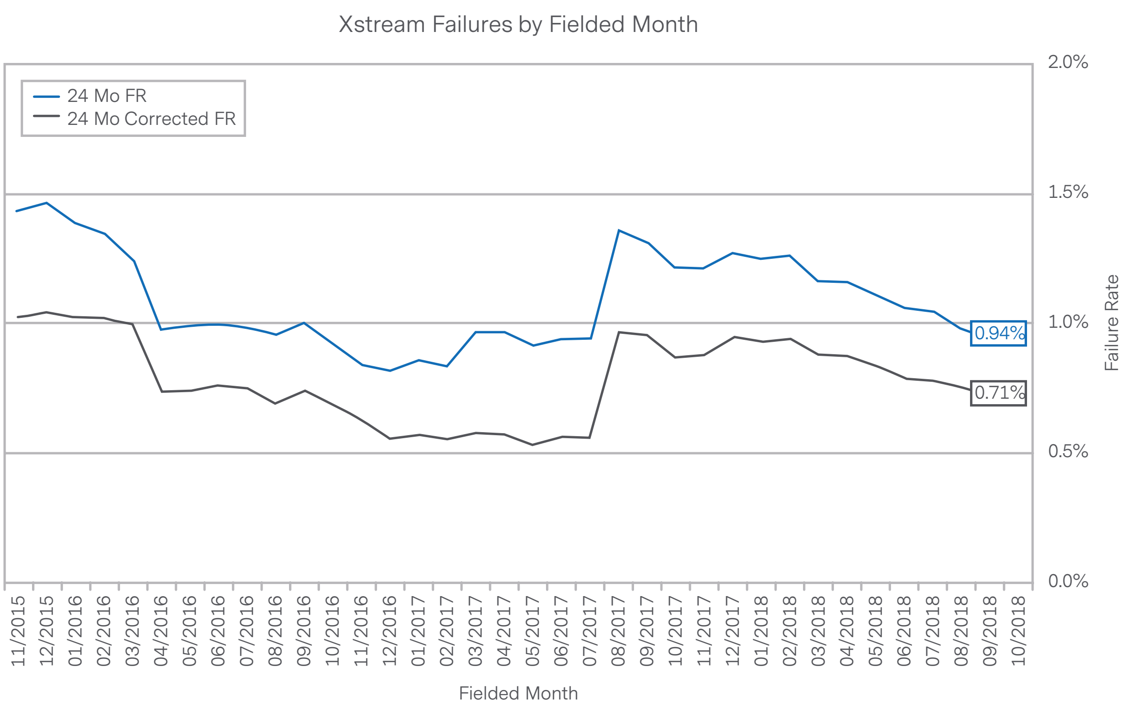
trace the use of RPS modules for CVD back to the need to keep CVD systems clean in-between processing wafers and to reduce particles. The impact of particles on yield is so overwhelmingly strong that this does not even warrant review. The purpose of RPS modules in CVD is exactly that – to eliminate the potential for particles in the CVD chamber and thus eliminate the possibility of putting particles on the wafer, which impacts yield.

For example, a 300 mm wafer with 500 logic devices or 2000 memory devices losing a few percentage points of yield equates to a loss of thousands of dollars on a single wafer; the consequences of an hour or a day of reduced yield compound the damage many times over. This is by far the strongest factor in most CoO models and is the case for RPS modules for CVD as well. RPS sources must not in and of themselves create particles. Later in this paper, we will address the case whereby RPS modules start to create particles as a result of the breakdown of the internal chamber coating. This factor limits the lifetime of the RPS chamber and is a key consideration in the CoO model.

Mean Time Between Failures

The impact of the next set of factors that we will look at varies from medium to strong, depending on the circumstances. Let's look at a few here – MTBF (related to AFR - Annual Failure Rate) and Average Repair Time, MTTI and Average Interrupt Time, and Chamber Replacement Frequency. The CoO model below considers these factors. Advanced Energy's Xstream Remote Plasma Source, used for chamber cleaning, has an AFR of less than 1%, as shown in Graph 1 below:



Graph 1. Advanced Energy's Xstream Failure Rate

One can use this to perform a direct calculation of MTBF, which is 876,000/AFR%, assuming that NTF (or "no trouble found") returned units have been removed from the population. If we assume an average repair time on the RPS is simply the replacement time (which is not always the case but can be used to simplify and would be worst case), then one can calculate average downtime (DT) per year associated with this failure rate.

Productive time could be assessed as "lost die per hour," which can typically run in the thousands of dollars per hour range. This factor would vary from medium to very strong, depending on the specific fab. To assess the downtime cost as the downtime (DT) of the CVD system which, for argument's sake, we call a USD five million capital cost depreciated over 60 months.

Systems today have a high MTBF. Because these modules are more reliable, the DT average per year associated with a "failure" is only on the order of an hour, as shown in the calculation in Table 1. At a net depreciation cost per hour of $114 ($5M over 5 years), this is a relatively small cost. However, if you looked at this DT as a cost of the lost die, this goes from a medium factor to a strong factor, depending on the size of the lost productivity per hour cost, which can run in the thousands of dollars per hour range.

Mean Time to Interrupt

One factor that may surprise engineers, and especially management personnel, is the MTTI and time to resolve interrupt DT number. As seen in Table 1, competitive RPS units typically have lower MTTI due to ignition and plasma instability issues over the life of the unit, due to changes in the chamber load over time as compared to DT numbers associated with "failures."

Because of the attention to ignition reliability as well as plasma stability, the Advanced Energy Xstream has very high MTTI. Xstream utilizes a variable frequency matching capability that reduces plasma instability when compared to competitive RPS systems. Again, as in the analysis related to DT associated with MTBF, the MTTI DT factor can go from medium to strong, depending on the cost associated with downtime. MTTI DT numbers are typically higher than MTBF DT numbers.

Chamber Replacement Frequency and Cost

RPS modules can generally last for thousands of RF hours. Suppliers typically use an aluminum oxide coating to protect the chamber against the harsh NF3 plasma utilized for chamber cleaning. The breakdown of the chamber coating depends on the base material utilized as well as the method of creating the aluminum oxide. Xstream, for example, utilizes a very high-quality base material in conjunction with an anodized surface to create a very long-lasting coating, showing lifetime results of more than 6000 RF hours, depending on the environment. Further detail on the use of base material, cooling, and anodization will be provided later, when we address design considerations for extended chamber lifetime.

Some coatings created on a lower-quality base material such as plasma electrolytic oxidation (PEO) and often used in competitive RPS products, show a reduced chamber lifetime when compared to Advanced Energy's anodized coatings solution. These chambers are found to last 3000 RF hours or less. Although less expensive to manufacture when compared to anodized coatings and high-quality base material, this breakdown requires chamber replacement, which comes at a cost of "failure" DT as well as chamber replacement costs.

All RPS modules must be evaluated over time to ensure chamber replacement as the coating wears. The outcome of a worn chamber is particle shedding, which should be avoided. As was discussed earlier, particles can significantly decrease yield and must be avoided at all costs. One of the promising areas of development in the industry today is predictive maintenance. Advanced Energy is improving the ability to gauge the variation and decline of certain RPS parameters to predict worn chambers, thus avoiding the catastrophic elements and their effect on yield.

As is shown Table 1, the impact of a more frequent chamber replacement, despite a lower replacement cost, is a higher average operating cost. Of course, the "failure" associated with chamber breakdown is already calculated into this model due to the MTBF, but the impact of the actual chamber replacement cost can be significant regardless of the cost of DT issue associated with the "failure" DT referenced above.

The final factor with a strong influence on the cost of ownership is the capital cost. Not to be diminished, of course, but the difference in the above factors easily outweighs a 20% or even 50% capital cost difference. These systems can last longer than five years and the ongoing costs for DT and chamber replacement can easily be made up in one to two years of service, as shown below:

	Xstream	Alternative Product	Comments
AFR	1%	3%	Typical Xstream vs. alternative product
MTBF	876,000	292,000	Assumes four chambers per system
DT – Annual Lost Hours	.32	.96	
MTTI	10000	3000	
Annual Hours of Operation	8736	8736	
Annual Interrupts	0.8736	2.912	
Annual DT Lost Hours	1.7472	5.824	Assumes plasma instability interrupts MTTI and two-hour repair
Chamber Replacement Frequency	6000	3000	RF Hours
Annual Chamber Replacements	0.2912	0.5824	20% operating time
Annual Downtime per Replacement	2.3296	4.6592	Eight hours per RPS replacement
Total Annual DT Per System	4	11	
Total Cost of System DT	$503.30	$1309.89	Cost of DT is depreciated cost of CVD system, $5 M
Annual Cost of Chamber Replacement	$2,621	$4076.80	
Cost of Chamber Replacement	$9,000	$7,000	
Total Annual Additional Costs	$3,124.10	$5,386.69	

Table 1. Xstream vs. Alternative RPS solution

Part 3: Remote Plasma Source Design Factors Affecting CoO Parameters

The final part of this paper focuses on design considerations resulting in increased or decreased CoO. All the design factors below will be reviewed and related back to the underlying aspect of CoO. Most of these factors, as will become apparent, lend themselves to cost advantages or disadvantages. Understanding these trade-offs, in addition to their impact on CoO, helps to plan as to what is important in the CoO for remote plasma sources.

Chamber Base Material and Coating Application

Advanced Energy has spent a considerable amount of time and resources on the development of a pristine coating and base material that results in an extremely long chamber lifetime. A more thorough explanation of this development and results is provided Advanced Energy's Remote Plasma Source Chamber Anodization paper. Base material results in a surface which, when anodized, lends itself to a pristine coating that is less perturbed by temperature variations as well as exposure to plasma. A further finding of this development activity relates to the differential thermal expansion rates between the substrate and coating, which require a cooling system that minimizes the thermal mismatch and thus extends the life of the coating. Although the cost of this approach is higher because of the need to use a high-quality base material as compared to cheaper aluminum used in other approaches, the resultant chamber lifetime increase far outweighs the costs.

Another approach employed by some other RPS solutions is to use lower-grade base material with its normal surface roughness and defects. Due to these defects, an anodized surface would replicate these defects and thus would not withstand the plasma exposure, because the surface defects would allow for higher leakage current and plasma exposure into the base material, leading to increased cracking and degradation. To appropriately cover this rougher surface, suppliers have tried to use a plasma enhanced oxide, which has a better coverage aspect and results in a smoother texture on the base material as compared to anodization. The drawback to this approach is that the plasma enhanced oxide is a more porous film and results in a shorter chamber lifetime.

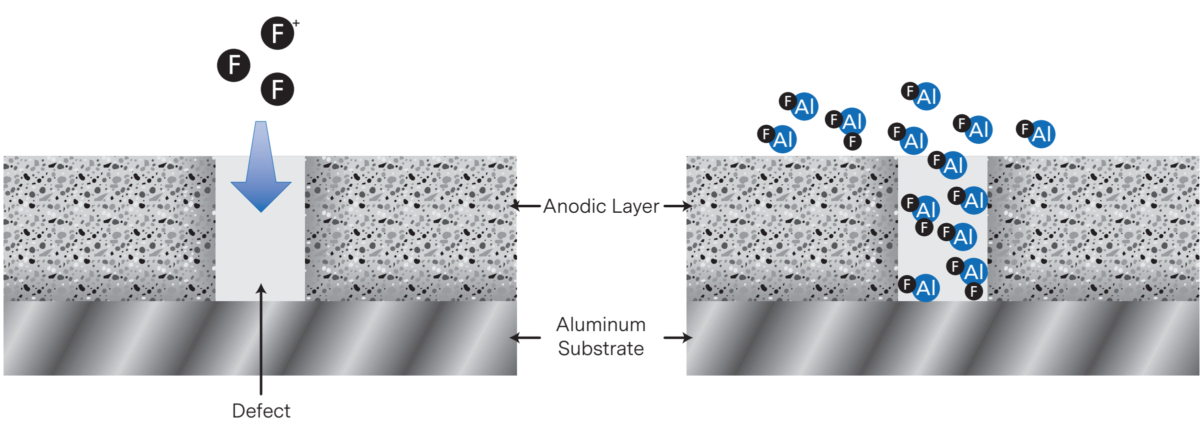


Figure 1. Cross section illustration of attack on the aluminum substrate by reactive species

These films are electrically leaky. It has been shown that with increased exposure to the high currents and voltages in plasma, the breakdown voltage of PEO starts to decrease and the leakage current increases, thus diverting some of the plasma power into the chamber wall. This loss of power results in lower etch rates in the chamber clean process itself. Ultimately, the chamber coating will break down and result in the shedding of particles into the RPS chamber, thus requiring a chamber replacement. The point is that skimping on the base material, although less expensive, results in a much shorter chamber lifetime as compared to a higher cost high-purity base material and anodization.

Chamber Cooling

Chamber cooling is required by all RPS systems to facilitate a longer chamber lifetime. The reason for chamber cooling is that the thermal properties between anodization/PEO and the base aluminum material are different (CTE - coefficient of expansion of aluminum oxide - is $4x10^{-6}$/°C; CTE of aluminum is $25x10^{-6}$/°C). If operating at a high temperature (above 150°C, for example), this thermal mismatch potentially will result in cracking the coating used and ultimately expose the base material to the plasma, which would cause chamber breakdown. The end effect of this is much like the previous problem, in which base material is exposed to fluorine, thus creating particles due to the formation of aluminum fluoride and particle shedding.

Advanced Energy has several patents on a cooling approach that results in chamber wall temperatures being maintained below 90°C, thereby avoiding the cracking and ultimate chamber demise.

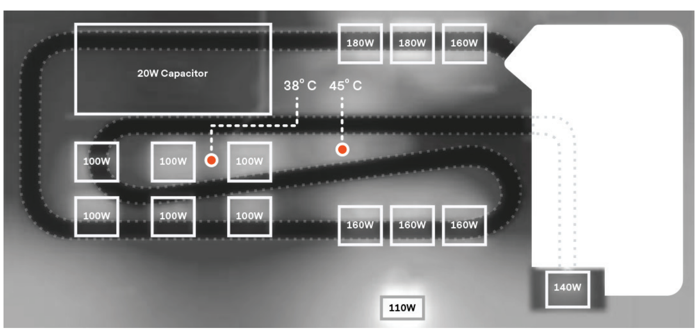


Figure 2. Cooling System Design and Temperature Test Results

Ignition

In Xstream, the magnetic core of the excitation transformer is placed around the vacuum chamber where the primary winding of the transformer is excited with RF; the electromagnetic field induced around the core sustains gas discharge within the vacuum chamber (Figure 3).

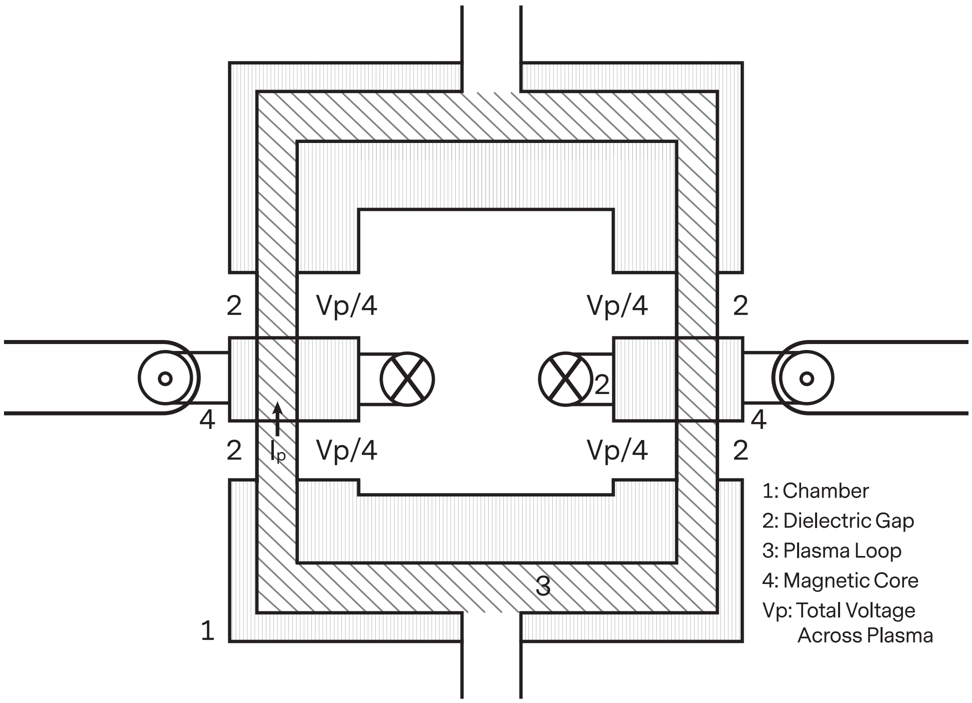


Figure 3. RF current and included field

The benefit of this type of approach has to do with the multiple points of ignition, although this does add to the cost of the chamber build when compared to other RPS chambers in which only one or two ignition points are used.

The excitation transformers distribute total induced voltage among the four dielectric breaks to prevent wall damage that can be caused by arcs or sputtering. Because there are four points of ignition, the potential for high voltage appearing across the dielectric gap causing arcs to occur is reduced, thus minimizing or eliminating the deterioration of the wall surface. With only one or two ignition points in other RPS systems, the voltage must be higher and creates a stronger likelihood of chamber degradation, which can be seen inside competitive chambers at the ignition points after as little as 1000 RF hours of operation. Of course, with chamber coating degradation comes the typical exposure of the base material to the fluorine plasma and, ultimately, particles.

Impedance Matching

Xstream incorporates an Active Matching Network as well as variable frequency tuning to ensure an accurate impedance match across a wide operating range. With this agility in design, the Xstream can accommodate changing loads in a process cycle, or long-term changes as the unit ages over time. Although this adds some complexity to the design, the overall CoO is reduced by the efficient use of power and the capability of the unit to adjust to changing environment and load impedance over the lifetime of the unit.

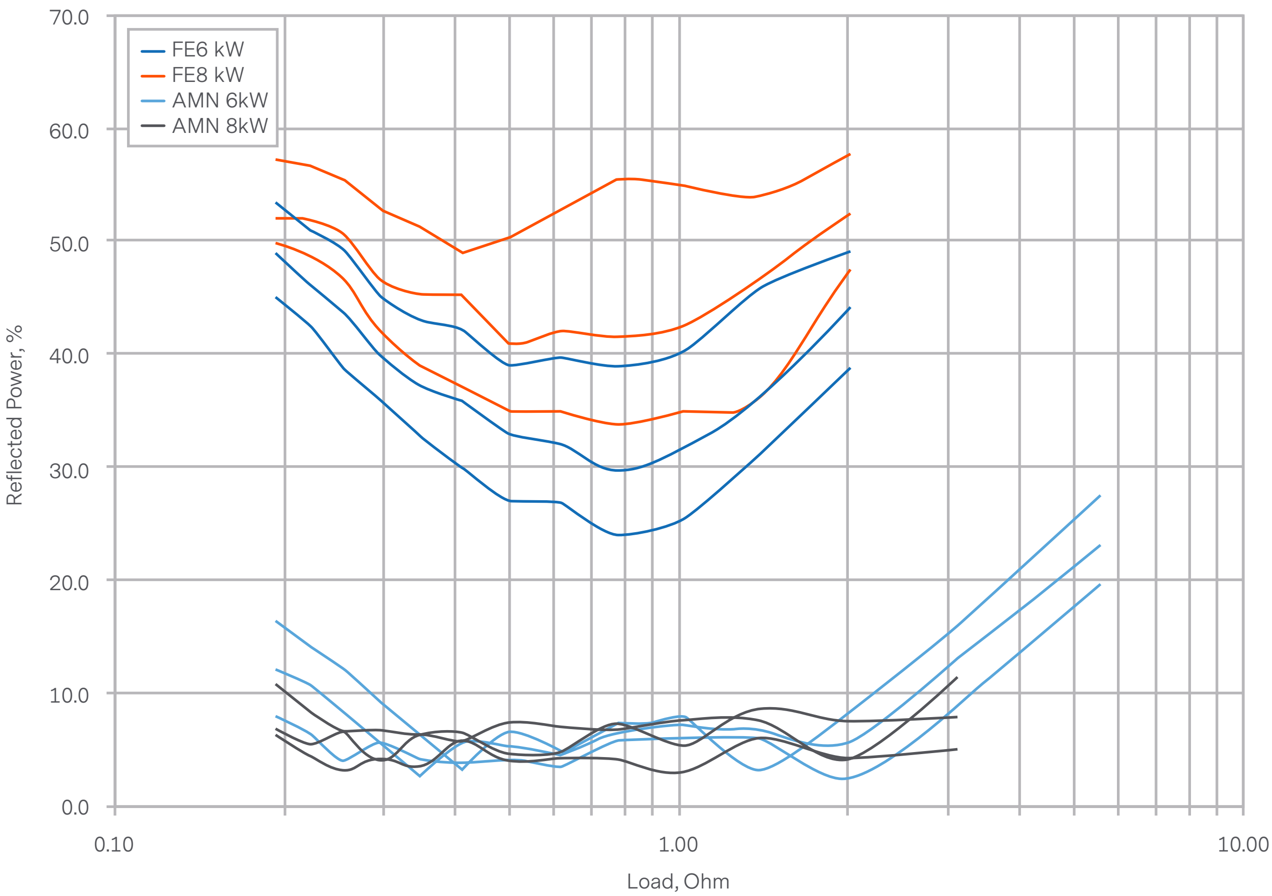


Figure 4. Reflected power for Rapid-FE vs Xstream AMN. Specified impedance range 0.5 – 2 Ohm

Power Delivery

Agile power control to a setpoint is achieved in the Xstream by a combination of a fast, solid state matching network, variable frequency, and ultrafast RF cycle-by-cycle power control based on real time plasma voltage and current measurements. Advanced Energy's patented technology enables accurate power control with maximum power efficiency under all process conditions. This allows the Xstream to be used as both a chamber clean and a wafer processing unit on one tool, eliminating the need for a second RPS in certain processes. Another advantage is that the Xstream can be used across multiple platforms with different performance needs, thus reducing variability and decreasing complexity across tools.

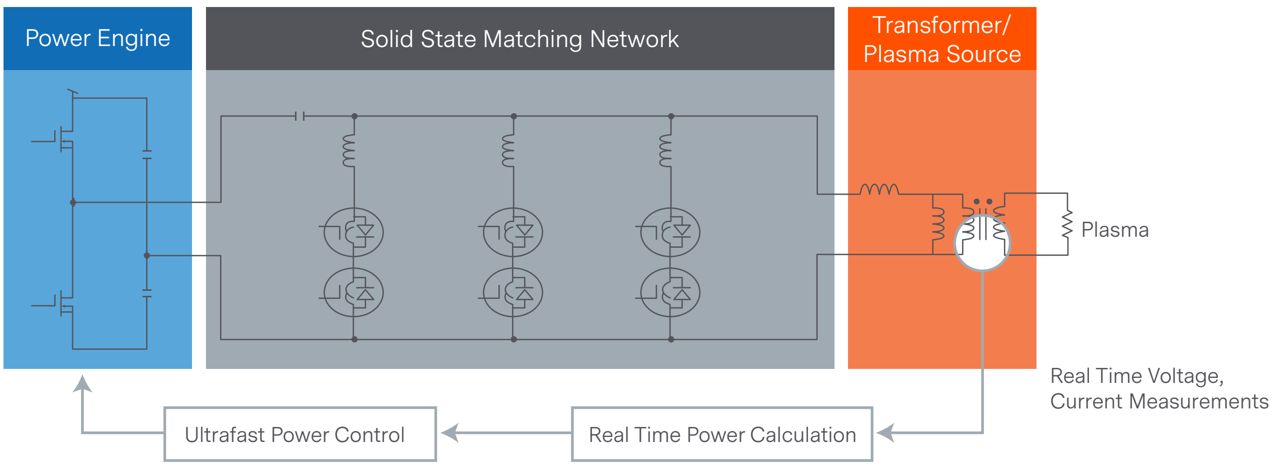


Figure 5. Agile power control to a setpoint

Conclusion

Cost of ownership can be a very complex and misleading topic. In the end, the customer must choose among the parameters of a cost of ownership model which impact them the most. Cost is the bottom line. For most customers, the most important aspect of a cost of ownership model is yield. Yield is typically the largest factor in a CoO model because it impacts lost die, which is a larger influence on cost of ownership than almost any other factor.

Comparative equipment costs between suppliers are usually driven by market factors and typically do not play a role. However, as can be shown by the analysis we've made, the cost to create a more robust chamber, improved ignition, higher reliability system does impact the cost to produce equipment. In the end, it is the ability to reliably produce particle-free plasma in support of chamber clean that will yield the best cost of ownership for the customer, so customers may be willing to pay more for a solution in order to get more reliable yield from their systems.

Advanced Energy's solution for chamber clean takes these steps to create longer chamber life, more reliable plasma and ignition, and thus a lower cost of ownership through a potential yield improvement due to these properties.

ABOUT ADVANCED ENERGY

Advanced Energy (AE) has devoted more than three decades to perfecting power for its global customers. AE designs and manufactures highly engineered, precision power conversion, measurement and control solutions for mission-critical applications and processes.

AE's power solutions enable customer innovation in complex semiconductor and industrial thin film plasma manufacturing processes, demanding high and low voltage applications, and temperature-critical thermal processes.

With deep applications know-how and responsive service and support across the globe, AE builds collaborative partnerships to meet rapid technological developments, propel growth for its customers and power the future of technology.

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