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# RF-based sensor technology improves cleaning efficiency on PECVD tools

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## ABSTRACT

Implementing an active RF sensor-based endpoint of PECVD chamber cleaning on several process tools in a wafer fab production line has demonstrated how this approach can reduce gas consumption and processing times, as well as increase tool throughput and improve on-wafer particle performance

## Introduction

Plasma cleans are commonly used in deposition processes to remove film buildup on chamber components. A typical plasma-enhanced chemical-vapor deposition (PECVD) tool consists of a multi-wafer chamber using a radio frequency (RF)-based plasma to deposit dielectric films on semiconductor wafers. The process performs film depositions on multiple wafers, during multiple deposition steps. During these steps, deposition material also blankets the walls of the process chamber and the process kit hardware. After the resulting plasma film accumulates to a certain level, it must be removed from the chamber walls and process-kit hardware before the next wafer is processed. If the dielectric film buildup is not removed completely and carefully, significant process problems can result, including high particle levels (due either to over-cleaning or incomplete cleaning), chamber kit wear from over-cleaning, and excessive clean-gas consumption. These problems, in turn, can lead to:

- Jeopardized film uniformity and thickness
- Reduced product yield and tool throughput
- Increased tool downtime
- Increased tool cost of ownership

Properly implemented plasma cleans increase the time between physical chamber cleans (also known as wet strip or wet clean), minimizing the aforementioned problems. Thus, a consistent means of determining the cleaning endpoint is needed to ensure optimal PECVD process functionality. However, once-ubiquitous endpoint

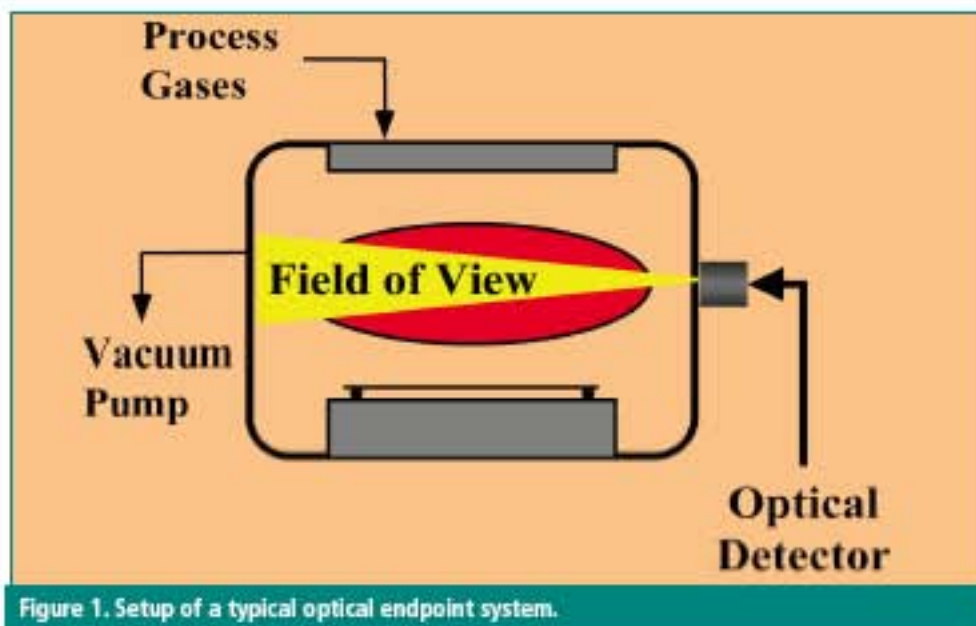


Figure 1. Setup of a typical optical endpoint system.

methods based on optical technology are fast reaching the limits of their usefulness.

This article details the implementation of active RF sensor-based endpoint of PECVD chamber cleaning on several process tools in a wafer fab production line. The results demonstrate how this approach can reduce gas consumption and processing times, increase tool throughput and improve on-wafer particle performance.

## Optical endpoint at its limit

The semiconductor industry has employed optical-based endpoint systems, i.e., systems utilizing optical spectroscopy, for over a decade. But with shrinking geometries and the advent of new process reactants, the optical method has reached the limit of its effectiveness.

Effective plasma cleans control particle generation by returning the chamber surfaces to their initial, pre-deposition condition. This accuracy and repeatability are increasingly difficult to achieve, due to the optical method's reliance on a transparent window into the process chamber. Over time, the window surfaces are altered due to chemical reactions occurring within the plasma, leading to inefficient cleaning. Furthermore, the window's small field of view does not provide adequate process oversight, as the film clears at varying rates throughout the chamber. Optical-based endpoint systems also do not perform satisfactorily when high-gas-flow or low-pressure conditions exist.

Figure 1 depicts the basic configuration of an optical spectroscopy endpoint system on a PECVD process chamber.

At a leading wafer fab, film removal had previously been accomplished with an in-situ RF plasma enhanced chamber clean performed between deposition steps. A chamber clean was run after a predetermined level of film accumulation in the chamber. This chamber clean process consisted of two separate cleaning steps: a  $C_2F_6$ -based high-pressure clean step, followed by a  $C_2F_6$ -based low-pressure clean step. The high-pressure clean process was terminated based on an optical spectroscopy-based endpoint detection system or an onboard time calculation program. The optical spectroscopy system (OES) determined when a chamber clean should be terminated based on an optical emission determination. The time calculation program used a predetermined deposition and etch rate. Based on the total time of deposition, the total time for etch was calculated and the length of the clean determined and implemented. The low-pressure clean step was always run to a set duration of approximately 300 s.

There are some inherent problems with this approach. First, clean time calculation programs are based on an assumed constant deposition rate and etch rate. When film is deposited on chamber walls and kit hardware, which consist of a variety of surface conditions and geometries, neither deposition nor etch rates are constant.

Secondly, etch rates are not linear.

They increase throughout an etch or clean process. Therefore, 20,000 angstroms of a given film does not require exactly twice as long to remove completely as 10,000 angstroms of the same film. Since deposition rates and etch rates are neither constant nor linear, inefficient plasma cleaning often results. Sometimes the chamber cleans run too long, resulting in substantial over-etching of process chamber and kit hardware, while at other times, the chamber cleans end prematurely and the film is not completely removed. As previously mentioned, inefficient plasma chamber cleans can lead to excess consumption of clean gas, increased downtime of process tools, undue chamber-kit wear, and unacceptably high on-wafer particle counts – ultimately, resulting in reduced product yield.

Based on these challenges and the questionable performance of the OES system, the fab in question sought a new approach to endpoint. The company turned to Advanced Energy for help, implementing AE's R.F sensor-based instrumentation.

### RF-sensor technology offers superior performance

RF sensor-based endpoint is based on the electrical impedance of the process chamber and plasma. Since the R.F sensor is in the R.F path, it is in electrical contact with the entire process chamber and kit hardware, as well as with the plasma itself. This results in very high sensitivity to the overall chamber and plasma impedance shifts that occur during chamber cleans. This sensitivity is independent of gas flow or pressure levels. Also, R.F sensor-based endpoint systems do not have the problem of small fields of view or the maintenance and signal degradation and variation problems associated with optical windows.

Figure 2 illustrates the basic configuration of an R.F sensor endpoint system on a PECVD process chamber, while Figure 3 compares signal output levels from an R.F sensor and an optical sensor on the same process tool. Note the large variation in the optical sensor output, both throughout the preventive maintenance (wet strip) cycles and across multiple wet strip cycles. The optical sensor output varies by as much as 37% throughout a wet strip cycle, and by as much as 75% from one wet strip cycle to the next. Conversely, the R.F sensor does not vary by more than 25%

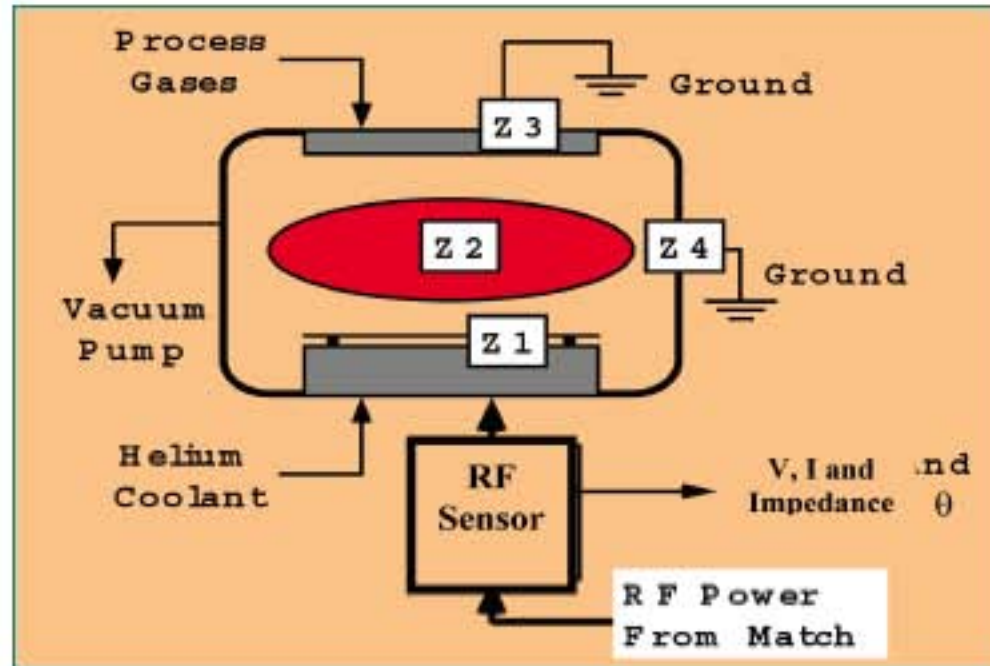


Figure 2. Setup of an RF sensor-based endpoint system.

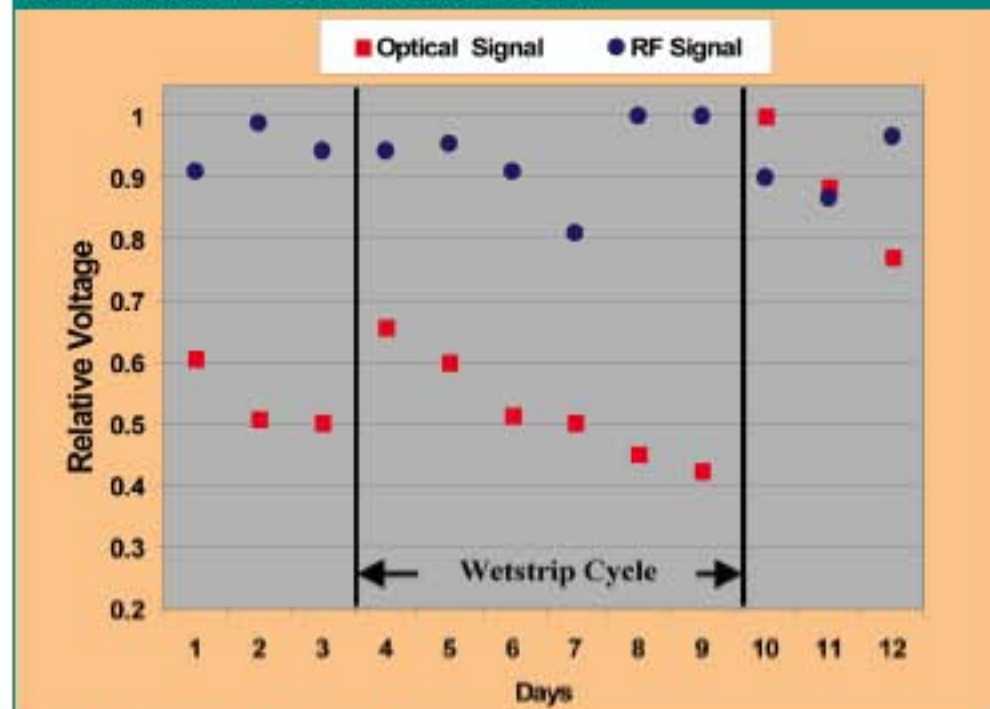


Figure 3. Comparison of optical vs. RF sensor output.

throughout a wet strip cycle or from one wet strip to the next.

The high sensitivity of R.F metrology enables accurate and repeatable process endpoint of in-situ plasma chamber cleans. At the beginning of a chamber clean process, the chamber and kit hardware are at a stable electrical impedance, at a given amplitude. As the chamber clean progresses and the film is removed, the electrical impedance changes as the chamber hardware begins to be exposed. Once the film is completely removed, the chamber, kit, and plasma impedance again stabilizes at a new amplitude. Therefore, the R.F signal changes, chamber clean endpoint, and termination can be easily identified and acted upon.

The R.F endpoint system utilized in this chamber clean endpoint

effort consists of an R.F sensor, its corresponding electronics box, and an R.F metrology software package that can be operated on either a standard desktop or a laptop computer. The R.F sensor contains current and voltage transducers, and is designed to survive the harsh conditions at the powered electrode without inducing process shifts in key process parameters. The sensor measures the fundamental and harmonic voltages, currents and phase angles of the process chamber, and plasma. The sensor is installed between the impedance matching network and the processing chamber. A block diagram illustrating this setup is shown in Figure 4. The R.F sensor is connected to an electronics box, which is in turn connected to a computer running the R.F metrology software. The R.F

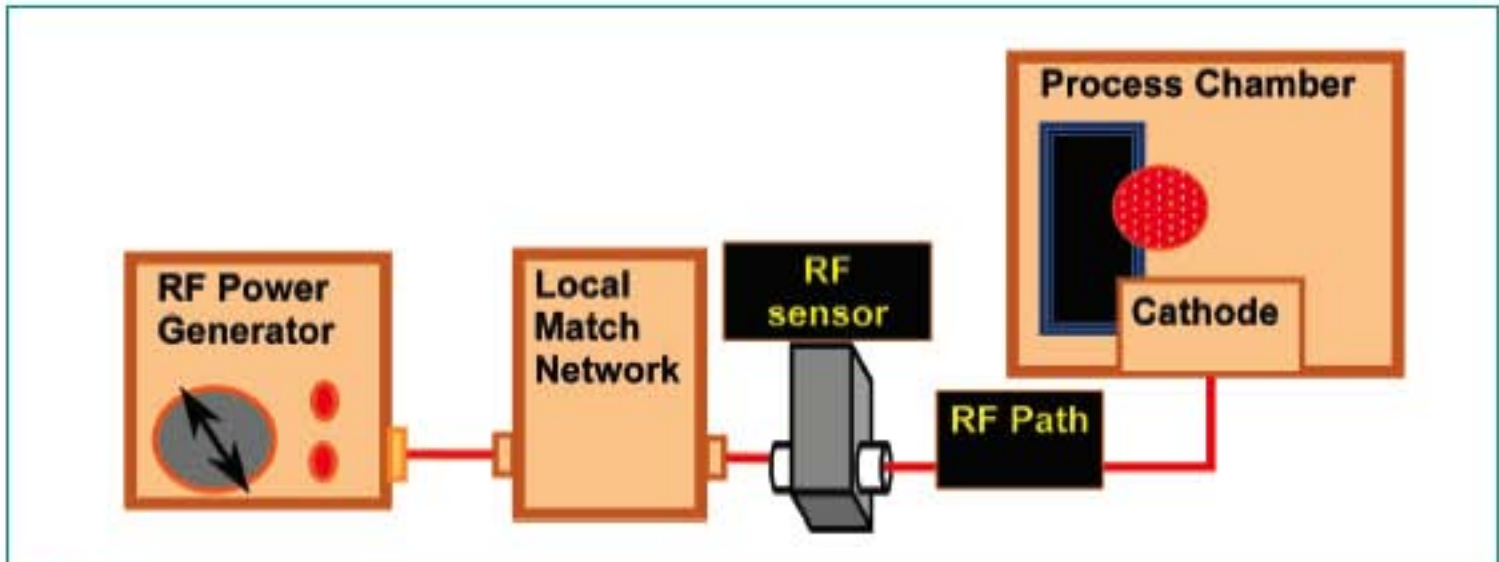


Figure 4. RF endpoint implementation.

metrology software allows for the viewing and storage of a multitude of R.F signals taken from the sensor. Data can be collected at a variety of user-defined rates to as fast as 10 ms.

This application focused on optimizing PECVD chamber cleans for accurate and efficient process termination. Both the high-pressure and low-pressure cleans were analyzed for improvement.

### Clean time evaluation

Initially, R.F endpoint systems were installed on multiple PECVD process chambers in production on the wafer fabrication line. The systems were configured for passive monitoring of the chamber cleans. Several thousand cleans worth of R.F-sensor data was analyzed. It was determined that the chamber cleans were less than efficient. Both the high-pressure and low-pressure clean steps showed substantial excess cleaning, or over-etching. As previously stated, this over-etching results in undue kit and chamber wear, excess clean gas consumption, increased particle levels, and decreased tool throughput.

Figure 5 depicts an R.F-sensor plot for one of the high-pressure chamber cleans. This particular high-pressure

clean step ran for 717 s. The clean step was terminated by the time calculation currently utilized by this particular PECVD process tool. The "X" and corresponding red drop-line at 501 s denotes where film removal was actually complete. This is where the chamber clean should have been terminated for efficient cleaning. Note that the R.F signal level has stopped transitioning at this point, and continues to remain stable throughout the remainder of the step. Therefore, the 216 s of processing that continued past this point was serving no useful purpose. In fact, this over-etching represents 216 s of costly wasted gas and tool processing time for every clean processed. It also represents 216 s of unnecessary chamber kit wear for every clean processed. Given the high cost of  $C_2F_6$  clean gas, process tool time and chamber kits, this 216 s of over-etching per clean translates to substantial dollar amounts.

Following analysis of the high-pressure cleans, an evaluation of the low-pressure cleans revealed that these steps showed no evidence of cleaning. This is consistent with the high-pressure evaluation results. Since the chamber is completely cleaned in the high-pressure

step, there is no film left to be removed in the low-pressure step. In the R.F plot of a low-pressure clean shown in Figure 6, note that there is no change in slope or amplitude of the R.F signal after the initial stabilization of the clean.

Also note in Figure 6 that the low-pressure clean is approximately 300 s. Here again, this is 300 s of unnecessary and costly wasted gas and tool processing time, as well as unnecessary chamber and hardware wear. It is important to remember that all low-pressure cleans run for 300 s, or 5 min, so this excess occurs in every chamber clean run.

### Clean time optimization

After the R.F analysis of both the high-pressure and low-pressure clean steps was complete, it was determined that the high-pressure clean endpoint should be actively determined with an R.F endpoint system, using a control algorithm that would terminate this step prior to an actual clean chamber condition. The low-pressure clean would then complete the chamber cleaning. This allowed for much more efficient chamber cleaning without the qualification of a new chamber clean recipe or process. The original plan-of-

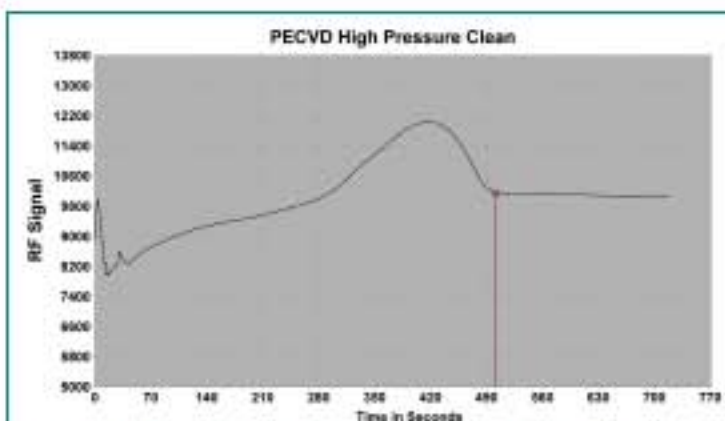


Figure 5. An RF-sensor plot for a high-pressure chamber clean.

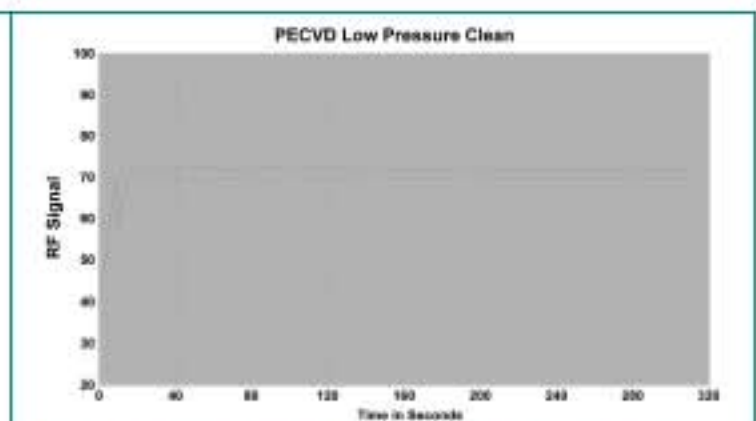


Figure 6. An RF-sensor plot for a low-pressure chamber clean.

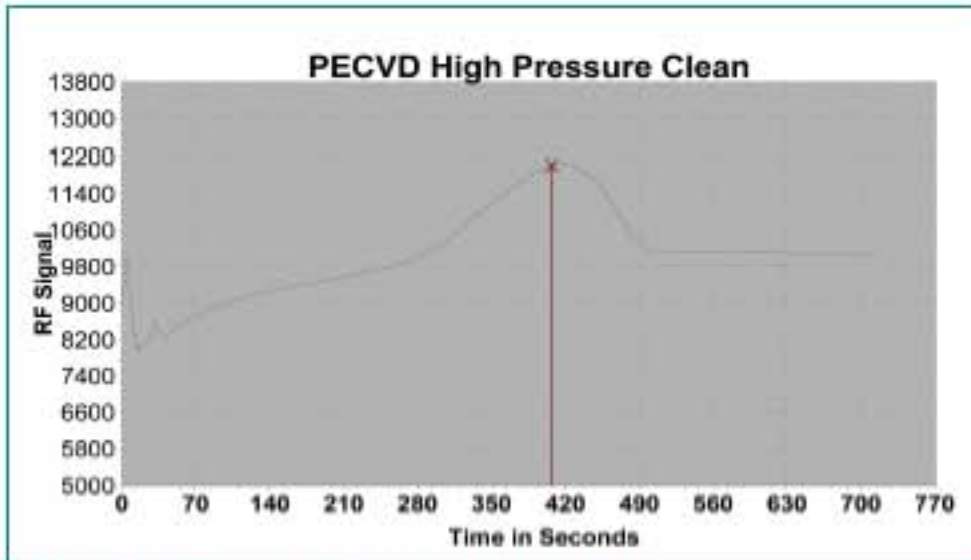


Figure 7. An RF-sensor plot for a high-pressure chamber clean.

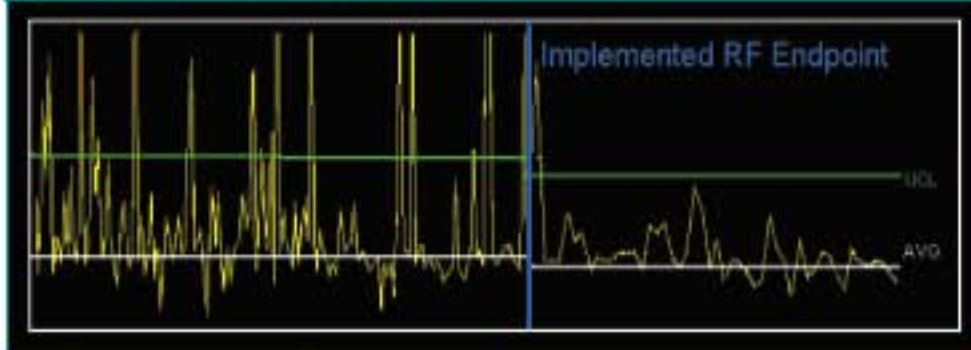


Figure 8. Particle performance chart from PECVD tool utilizing RF sensor-based endpoint system.

record (POR) chamber clean recipe was utilized, with the high-pressure clean being terminated by an RF endpoint system and its corresponding control algorithm software, as opposed to the time-calculation program utilized OR an optical endpoint system. As stated previously, the low-pressure clean step was left in its original POR state.

Figure 7 displays an RF plot of the same high-pressure clean step shown in Figure 5. Figure 7 however, denotes with a red drop-line where a new RF control algorithm could call endpoint. Note that the new RF algorithm calls endpoint at 407 s. This would result in a time savings of 310 s – more than 5 min – versus the original POR high-pressure clean time of 717 s. Again, all the cost and productivity benefits that result from this time savings are applicable. An additional benefit is the significant reduction in CFC emissions that is realized with such a dramatic reduction in  $C_2F_6$  processing time.

#### Active RF endpoint implementation

Upon completing the clean time optimization, the RF endpoint system was put into production on one tool in the wafer fabrication line. The tool was run for several months with the RF endpoint system active. Clean time and on-wafer particle performance data

collected and reviewed revealed a greater than 30% reduction in chamber clean times, as well as dramatic improvements in on-wafer particle performance. These results allowed the production line to realize 18% reductions in both the upper control limit on particle counts and the average number of adders per wafer. Furthermore, the standard deviation and the number of excursions in particle performance were also significantly reduced.

Figure 8 is an actual particle performance chart from this PECVD tool. Note the remarkable improvement in particle performance on the chart after the RF endpoint was implemented. RF endpoint implementation is denoted on the chart in blue. Post-wet-strip inspection after the implementation of RF-based endpoint revealed substantially decreased chamber wear. As a result, the production line increased its wet strip interval from 22,500 wafers to 27,000 wafers. This increase in wet strip interval will greatly reduce tool downtime and increase tool throughput.

Given these results, RF sensors and RF endpoint systems were installed and activated on all of the remaining PECVD processing tools in the production line. Since this proliferation, similar clean time reductions and on-

wafer particle performance improvements have been observed on all of the remaining PECVD tools in this production line. In fact, the lower on-wafer particle performance control limits and increased wet strip intervals placed on the first processing tool have been migrated to the remaining tools. The current plan is to continue to monitor particle performance and chamber conditions upon preventive maintenance operations. The belief, at this time, is that the on-wafer particle limits can be reduced and the wet strip intervals extended even further.

## Conclusion

This investigation of RF endpoint systems on PECVD chamber cleans has yielded notable results. The capabilities of RF endpoint systems to accurately and repeatably call endpoint on PECVD chamber cleans were clearly demonstrated. In addition, the RF endpoint systems installed and activated in this production line have led to dramatic processing time reductions and extended preventive maintenance intervals. As stated previously, reduced processing times lead to substantial savings in gas consumption, as well as increased tool throughput and overall tool capacity. Increased preventive maintenance intervals also lead to increased tool throughput and capacity and decreased overall operating costs. Finally, the importance of better on-wafer particle performance and reduced CFC emissions realized with active RF endpoint cannot be overstated. It is important to realize that there is still room for further clean optimization on the low-pressure clean steps. It is also important to note that the extent to which the preventive maintenance intervals can be extended has not yet been fully realized, but it's clear that this RF sensor-based technology offers exciting opportunities for further process improvements.

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