MICRO
Defect Reduction and Yield Enhancement Strategies for Semiconductors and Advanced Microelectronics

Achieving process understanding and real-time fault detection on a PVD tool

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The increasing demand for fewer defects, higher throughput, and cost reductions in semiconductor processing has sparked steady interest in advanced process control (APC). Many companies are evaluating APC's potential to increase capacity while investing little capital. This article focuses on how a major Asian semiconductor facility increased its process understanding of a physical vapor deposition (PVD) tool. The study involved a control package on a PVD tool that was equipped with six sensors. This setup enabled company engineers to characterize previously unknown details of the process and prevented wafer misprocessing through active fault detection.

A control system attached to a PVD tool can be used to customize recipes during process development, perform process monitoring to detect misprocessed wafers, and optimize PM cycles.

The heart of the APC system in this installation was the FabGuard control package from INFICON (East Syracuse, NY). FabGuard collects data from integral as well as add-on sensors and analyzes the data using advanced statistical and modeling techniques. By comparing an active process with a model developed from previous runs, the system can detect excursions from acceptable processing, detecting faults with minimal false alarms. At the fab where this study was conducted, the control package was installed on an Endura 5500 from Applied Materials (Santa Clara, CA) through the tool's secondary SECS

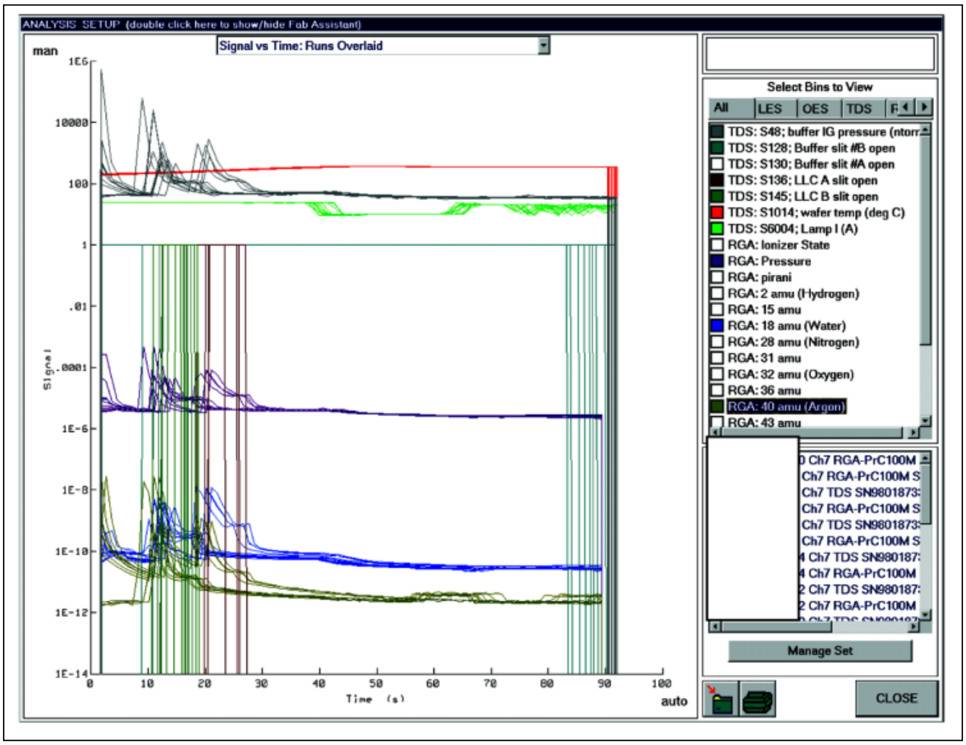

Figure 1: Degas data collected from a 25-wafer production lot illustrate normal process parameter profiles. The data demonstrate how the water peak (blue line) increased approximately two decades each time the loadlock doors opened (dark green and dark brown vertical lines).

port. The tool was equipped with two aluminum-silicon-copper metal deposition chambers, a preclean chamber, and two degas chambers. Each of these chambers had active residual gas analysis (RGA) sensors, and the preclean chamber also had a particle monitor. After performing a series of wafer runs to characterize the system, the engineers had a picture of the process, which they could compare with process improvements and which they could use as a baseline to detect process excursions.

The system distinguished between wafer types and chambers and stopped processes when resist removal was incomplete.

Establishing Baseline Values

To provide a baseline for controlling the PVD process, the engineers first took a fingerprint of each chamber. They ran several production lots through each chamber and used the control package to collect data from the tool sensors, RGA sensors, and particle sensor. Figure 1 shows the normal process parameter profiles from one of the degas chambers. The box on the top right of the screen ("Select Bins to View") allows users to plot data from a specific sensor and provides the key to the data in the chart. Items labeled "TDS" indicate data coming from the tool controller. Figure 1 demonstrates how the water peak (represented by the blue line) increased approximately two decades each time the loadlock doors opened (represented by the dark green and dark brown vertical lines). Opening the cooling chamber slit had a similar effect (represented by the ocean blue vertical lines).

Once the engineers had completed the fingerprinting process and established baseline values, they could begin to compare those values with subsequent processing results. During the relatively short period in which this study was conducted, they were able to distinguish between incoming wafer types and chambers, reduce overall processing time, and detect and stop processes when resist removal was incomplete.

Experimental Results

The Effect of Wafer Substrate Type. One of the engineers' first findings was that thermal performance differed between runs. After several runs, it was apparent that that difference was related to substrate type: epitaxial wafers demonstrated significantly higher levels of thermal oscillation than nonepitaxial substrates under the same degas recipe conditions. Examining the data more closely, the engineers discovered that the epitaxial substrates experienced an overshoot of approximately 30°C while the nonepitaxial substrates experienced an overshoot of only 10°C, as shown in Figure 2. Although the thermal plots from both substrate types oscillated, they oscillated at different frequencies and amplitudes. The epitaxial substrates oscillated 8°–12°C every 20–25 seconds, while the nonepitaxial substrates oscillated only about 1°C and at a higher frequency.

These detailed data enabled the engineers to investigate the impact of the different substrates and customize the temperature-control coefficients for each substrate type to achieve the highest yield. As a result of this investigation, the engineers created a new recipe for degassing epitaxial substrates.

Characterizing Chamber Differences. Using the control package, the engineers were able to compare the two degas

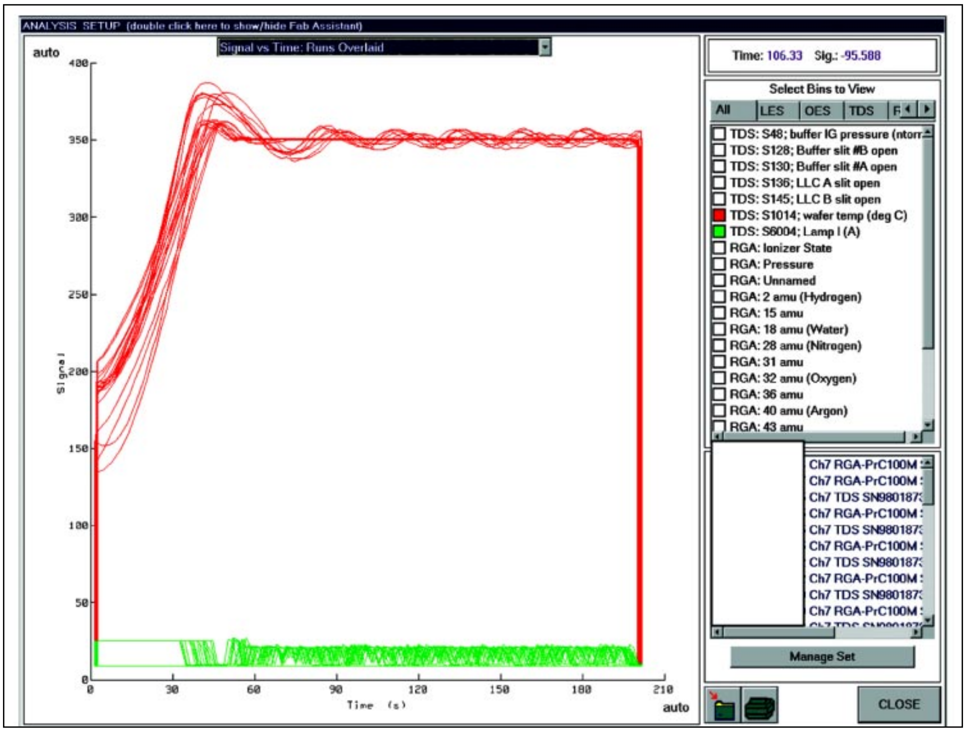

Figure 2: The thermal response of epitaxial substrates differs from that of nonepitaxial substrates using the same degas recipe. The epitaxial substrates (oscillating profile) experienced an overshoot of approximately 30°C, while the nonepitaxial substrates (straight profile) experienced an overshoot of only 10°C.

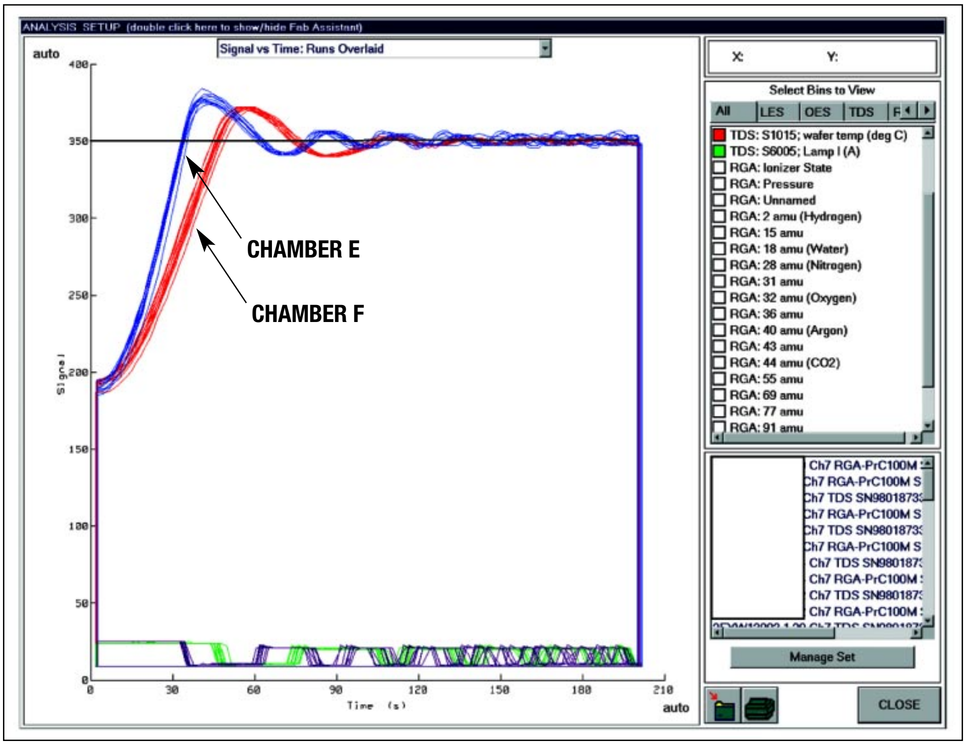

Figure 3: Comparison of data from two different degas chambers using the same recipe.

chambers. Figure 3 shows the thermal response from the two degas chambers using the same recipe of 350° for 200 seconds. To be certain they were examining chamber differences and not substrate or other preprocessing differences, the engineers split a lot and ran half through one degas chamber and half through the other. With all set points the same, the thermal response of the two chambers differed significantly. This difference also affected the RGA data from the two chambers. The control package corroborated the differences between the two chambers by analyzing the ion currents for masses 55, 77, and 91.

The control package also allowed the engineers to investigate why the two chambers functioned differently. By analyzing the lamp current profiles at the bottom of the chart (purple and green traces), it was determined that the lamps cycled at different times throughout the process.

Preventing Wafer Misprocessing. Combined with RGA sensors, the control package can identify wafers that have undergone incomplete photoresist removal and prevent them from entering the PVD chamber. The package looks for masses that correspond to the organic compounds in photoresist. When one of these compounds is identified, the system activates an alarm and sends a stop-processing signal to the tool controller.

To test the control package's ability to detect photoresist and test for false alarms, the engineers conducted an experiment using completely ashed wafers, wafers that had undergone 90% photoresist removal, and wafers that had undergone only 50% photoresist removal. A clean TEOS wafer was processed between each contaminated wafer run.

The engineers investigated masses 15, 48, 77, and 91. When the signal intensity of mass 15 was $>5 \times 10^{-10}$, mass 48 was $>8 \times 10^{-11}$, mass 77 was $>2 \times 10^{-11}$, and mass 91 was $>2 \times 10^{-11}$ A for five data points between 90.2 and 182.87 seconds into the run, the control package activated a yellow (moderate) alarm. When the signal intensity of mass 15 was $>1 \times 10^{-9}$, mass 48 was $>2 \times 10^{-10}$, mass 77 was $>5 \times 10^{-11}$, and mass 91 was $>5 \times 10^{-11}$ A for five data points between 90.2 and 182.87 seconds into the run, the control package activated a red (critical) alarm. These signal intensity limits were calculated from the product wafer data stored in the database. The analysis was activated between 90.2 and 182.87 seconds into the run because the wafer must be heated long enough so that the relatively large molecules present in photoresist organics can be released from the wafer surface.

Figure 4 presents the data from three wafers in the experiment. The first run (represented by the data in the first third of the graph) involved a clean TEOS wafer. Since the signal intensity of three of the masses remained below the alarm limits, no alarm was activated. The second run (represented by the data in the middle third of the graph) involved the 50% ashed wafer. The control package activated the red alarm 109 seconds into the degassing step, because the signal intensity of all four masses exceeded the red alarm limit. After the 50% ashed wafer was processed, a clean TEOS wafer was run (represented by the data in the last third of the chart). Residual resist gases in the chamber caused the signal intensity of all four masses to exceed the yellow alarm limit. These results indicate that the control package detects cross-contamination during normal processing.

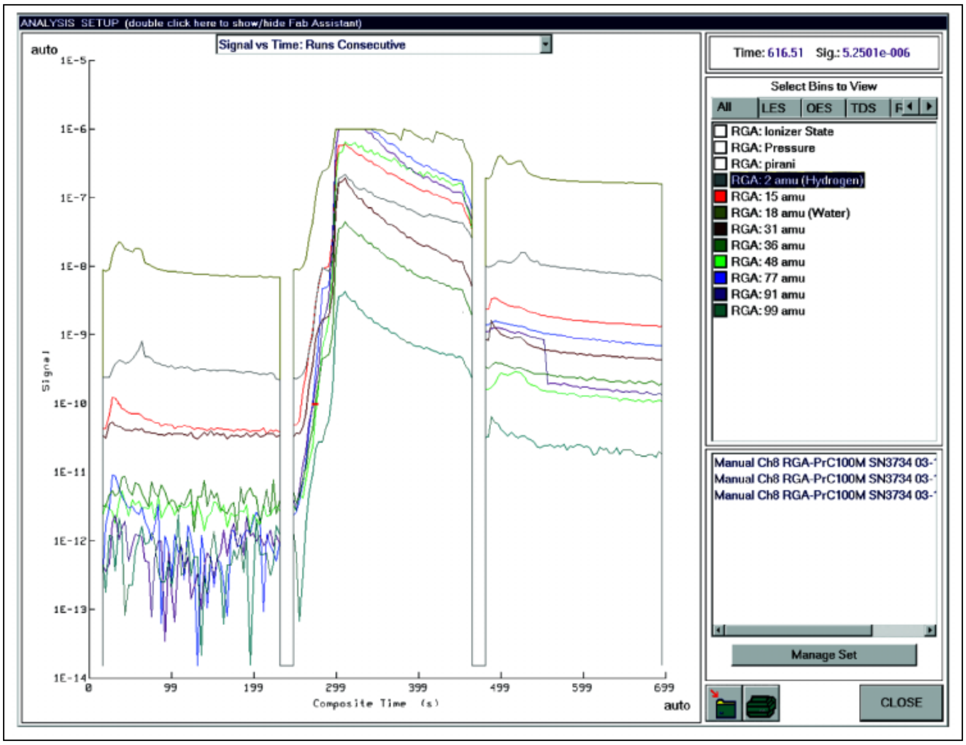

Figure 4: Comparison of the performance of three wafers. The first run involved a clean TEOS wafer, which did not activate an alarm. The second involved a 50% ashed wafer, which activated a critical alarm. The third was a clean TEOS wafer, which activated a moderate alarm because residual resist gases remained in the chamber.

The control system was used to reduce the degas recipe from 200 to 120 seconds with no adverse effect.

Degas Process Optimization. Lamp power and time are the two critical parameters in a degas recipe. Both are related to each other and should be optimized. Lamp power must be set high enough to heat the wafer to the target temperature, but it must not be set too high, since rapid heating can alter the electrical characteristics of previously fabricated layers. Degas time must be long enough for moisture and hydrocarbons to be desorbed from the wafer surface, but once moisture and hydrocarbons have been desorbed, extra degas time lowers tool throughput.

A common degas recipe used at the fab where this study was conducted heated the wafer at 350°C for 200 seconds. To maintain that temperature, represented by the red line in Figure 5, the lamp cycled on and off, as represented by the green line. Excluding events caused when the loadlock and cooling chamber slit valves opened, the water and hydrogen profiles were virtually flat beyond the initial 90 seconds of processing.

After determining that only 109 seconds were required to detect the presence of photoresist in the chamber and only 90 seconds were required to complete the degas step, the engineers decided that the full degas recipe of 200 seconds was excessive. Consequently, the step was reduced to 120 seconds with no adverse affect—a 40% reduction in degas time that contributed to an overall throughput improvement.

Verifying Pumpdown Performance in the Preclean Chamber. Monitoring pumpdown in any chamber can help to ensure that maintenance is performed at correct intervals. By monitoring for the presence of hydrogen, for example, engineers can determine when cryopump performance begins to degrade, indicating the need to regenerate the pump.

Figure 6 demonstrates that particle counts (represented by the green lines) fell slowly when pressure (represented by the red line) decreased during the initial pumpdown. After the initial pumpdown, the chamber was purged with nitrogen for 15 cycles. Each time the nitrogen came on, there was a corresponding particle spike (center of the chart). After the nitrogen purge cycle was complete, however, particle counts fell significantly.

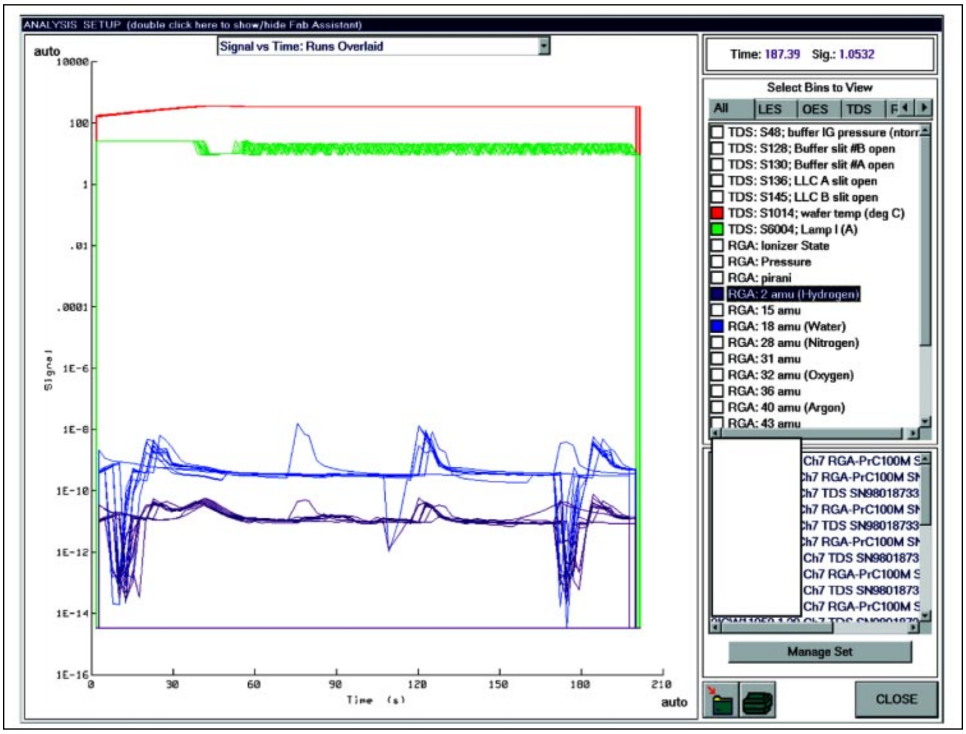

Figure 5: Data showing a common degas recipe, in which wafers are heated at 350°C for 200 seconds. The water (blue) and hydrogen (purple) profiles were virtually flat beyond the initial 90 seconds of processing.

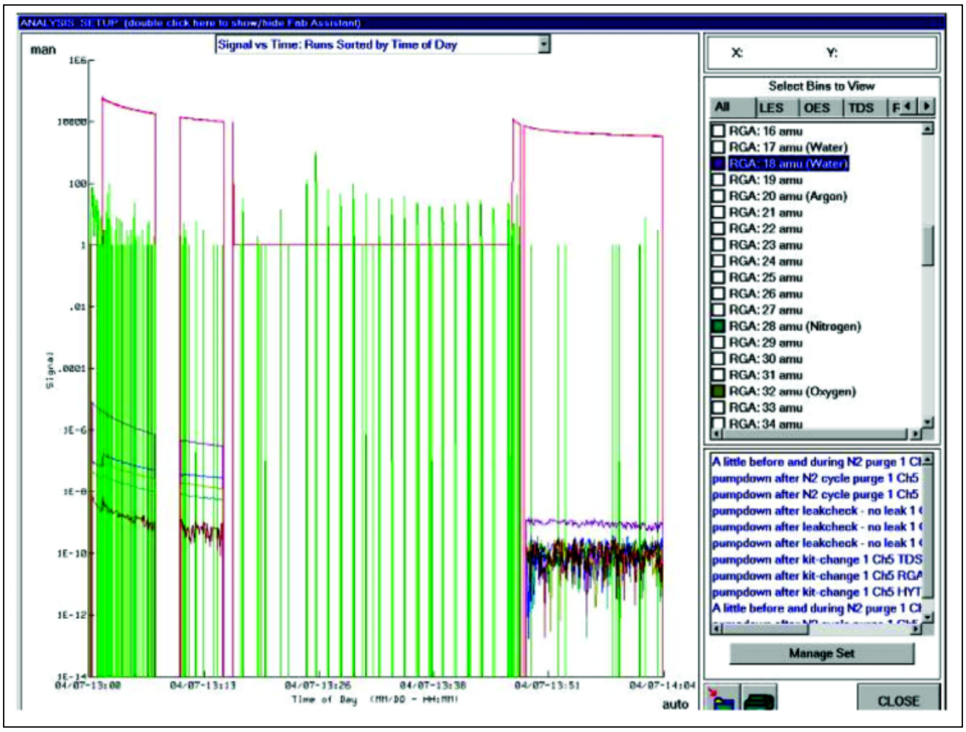

Figure 6: Data demonstrating that particle counts (green lines) fell slowly when pressure (red line) decreased during the initial pumpdown. During nitrogen purge, particle counts increased intermittently (green spikes at center of chart). But after the nitrogen purge cycle was complete, particle counts fell significantly.

The engineers also were able to investigate particle counts before and after preventive maintenance was performed. In the 25-wafer lot processed before preventive maintenance, 11 wafers had particles. In fact, one wafer had as many as 50. After preventive maintenance, particles were detected on only 9 wafers out of the lot, none of which had more than 10 particles.

Optimizing PVD Bake-Out Times. After preventive maintenance is performed on a PVD chamber, the chamber must be baked to expel the moisture and contaminants that collect in it while it is exposed to the atmosphere. Chamber bake-outs, including bake and cool-down cycles, typically last six to eight hours. Any reduction in bake-out times would significantly improve tool use. Consequently, the engineers decided to use the RGA data collected from the PVD chamber to investigate what happened when the PVD chambers were baked for a specified length of time at a specified temperature, and to determine what could be done to reduce bake-out times.

First, the engineers reduced the sampling rate of the control package to every two seconds in order to compress the six-hour processes on the screen. Figure 7 shows the data from a six-hour bake-out at 100°C. The very slow decrease in the water signal (represented by the blue line) indicates that the temperature was not high enough to expel the water from the chamber. A six-hour bake-out at 100°C would still leave a significant amount of water in the chamber. However, additional testing indicated that shorter bake-outs at higher temperatures can remove most water from the chamber.

Second, the engineers investigated how the cooling water affected the bake-out. Data from the control package demonstrated that the chamber outgases more rapidly when the cooling water is left off during the bake-out process. Additional experiments should make it possible to further reduce bake-out times, perhaps to as little as 1.5 hours. Because the control package can monitor residual gas profiles, it can stop the bake-out when the profiles show that the chamber is qualified to specifications. This monitoring helps to reduce preventive maintenance times, thereby improving machine uptime.

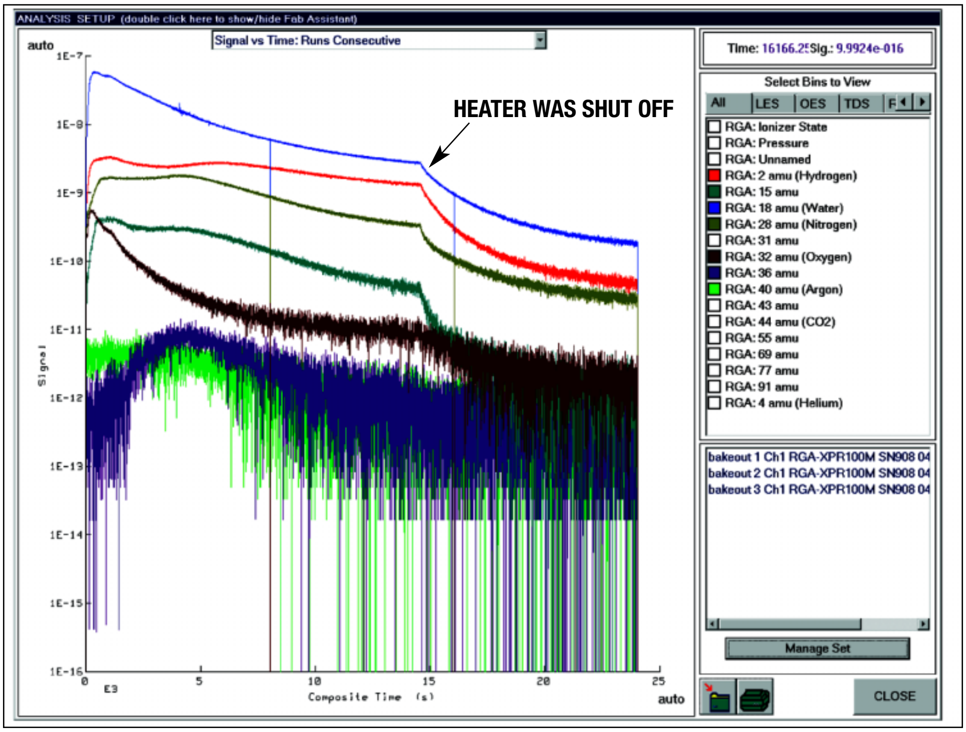

Figure 7: RGA data showing the results of a six-hour bake-out at 100°C. The slow decrease in the water signal (blue line) indicates that the temperature was not high enough to expel the water from the chamber.

Conclusion

The control package discussed in this article can be used to perform a range of functions in semiconductor fabrication. During process development, the package enabled engineers to customize degas recipes to obtain the same temperature profile for epitaxial and nonepitaxial wafers, as well as for different devices and layers. These recipes can be improved to provide increased throughput without risk of reduced wafer quality. The engineers also investigated performance differences between different degas chambers. Because the temperature and duration of the degas process can affect the physical nature of wafers, control strategies are required to understand and control these process variables.

In a production setting, the control package performed process monitoring to detect misprocessed wafers before they could cause cross-contamination. It may be possible to set alarms to detect faults associated with specific product wafer types.

Further tests were performed to optimize preventive maintenance cycles. Using control software, maintenance engineers can adjust schedules based on actual system performance and improve maintenance procedures to shorten downtime without sacrificing equipment reliability. The initial work presented in this article can lead to process enhancements, effective equipment-troubleshooting techniques, and cost reductions.

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