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Enhanced process metrology using plasma parameters in FDC

EXECUTIVE OVERVIEW Automotive device manufacturers have to meet increasing levels of quality as their customers demand a zero defects quality level. However, quality and reliability at reasonable costs require excellent process control, particularly for plasma etch and deposition. Production tools provide a large amount of data, but most of them characterize the tool hardware instead of the process. Using additional sensors and an efficient data management system provides a significant benefit and closes the gap between process and tool data.

New technologies and increasing demands for quality from customers require new control methods beyond the traditional ones. "Frozen" processes are often no guarantee of reliability and quality. One can freeze the recipe in the tool, but one cannot freeze the plasma state; it depends also on the state of the chamber wall, which cannot be characterized by tool parameters.

Often, small process deviations cause yield loss or device parameter excursions, and there is no system in place that aborts the process. The more complex the technologies, the more sensitive the products are to small process deviations. As plasma processing is the heart of device manufacturing, our focus is on the evaluation of small deviations in that process, so additional parameters are needed that describe it as precisely as possible. Before we come back to this issue, we will discuss how data is collected and automatically and efficiently analyzed. Finally, we will show how to improve the results by using additional sensors that provide plasma parameters.

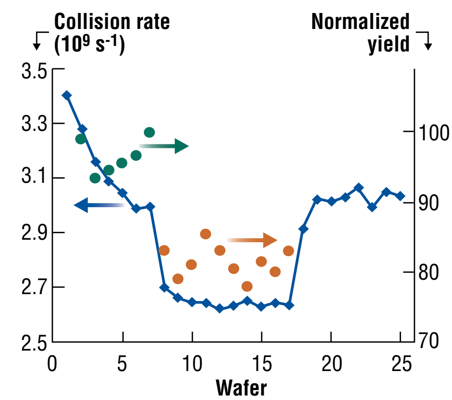

Figure 1. An example of a defective capacitance manometer causing a shift of real pressure and finally electron collision rate. The tool did not abort the process because the defective device fooled the tool with a "correct" pressure.

Setup of the FDC system

From the beginning of the fault detection and classification (FDC) implementation some years ago, the advanced process control (APC) group has collaborated closely with the process integration and process departments. The main goals were 1) to improve product quality, in particular for automotive products through a zero defects program; 2) to improve inline yield; and 3) to increase process stability and tool productivity.

To achieve these goals, the fast and efficient FDC approach was chosen to avoid excursions and disasters, reduce cost of test wafers, transition from preventive to predictive maintenance, and improve safety of maintenance personnel. Micronas currently integrates etch, diffusion, implant, and thin film deposition tools into Maestria, which is the FDC software from PDF Solutions.

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Process control strategy

In the past, many process parameters were monitored without any knowledge-based weighing. Unfortunately, small process deviations in new technologies often disclose their influence on device parameters very late in the manufacturing cycle, and device failures were not detected until final test. The accumulation of several tool parameter deviations near the specification limits can also cause subsequent process excursions. Therefore, a weighing of parameters into two classes is recommended.

The first class comprises only key parameters, which are mostly process-related. The second class includes parameters away from the real process. If parameters in the first class indicate a fault or deviation, the cause of the excursion can then be found with the help of the large pool of parameter data in the second class.

Key parameters are characterized by 1) a higher sensitivity than the product; 2) a logical meaning that enables easier root cause analysis; 3) an indication of which second-class parameter is responsible for the problems; 4) showing all process and product relevant changes immediately; and 5) their plasma-physical background and model-based determination.

For the majority of tool faults, a univariate control for the key parameters is sufficient. (The univariate control deploys simple limits for single parameters.) Conversely, multivariate control takes several parameters and their dependencies into account, and needs a more or less complex model. The multivariate control is a helpful and easy approach to identify new and unknown tool deviations from a classified standard tool state.

Insufficiency of tool parameters

The plasma process also depends on hardware aging, as the condition of the chamber wall cannot be characterized by tool parameters alone. The tool parameters characterize the tool, but not the plasma process. In addition, there may be hidden tool faults that cannot be detected using standard tool parameters. The tool controls one of the most important process parameters—process pressure—through a capacitance manometer. If this pressure sensor provides an incorrect value, then the process does not run at the correct pressure. If there is no second pressure measurement, as is often the case, then a tool fault by a drifting capacitance manometer cannot be detected. **Figure 1** shows an example of a defective capacitance manometer causing a shift of real pressure and finally electron collision rate. The tool did not abort the process because the defective unit fooled the tool with a "correct" pressure.

Using plasma parameters such as collision rate is the only means to indicate process variations. The deviation of the nitride etch process at collision rates lower than 2.8×10^9 have been shown to lead to problems with endpoint detection and can be significantly related to the yield as shown in Fig 1. As already stated, most tool parameters are not sensitive enough for changes or drift inside the chamber as it can be easily found for the pressure. In accordance with the ideal gas law, the density of neutrals is

$$n_n = \frac{p}{k_B T_n}$$

where p = pressure, is an adjustable tool parameter, n_n = the density of neutrals (a crucial process parameter), T_n = gas temperature (a hardware parameter for chamber temperature), and k_B = the Boltzmann constant.

The equation illustrates that the highly important parameter—the gas density—depends on pressure as well as gas temperature. Unfortunately, the gas temperature is unknown, but it can affect the process significantly (e.g., through instabilities as the so-called first wafer effect). Strictly speaking, a constant pressure and an increasing gas temperature in the chamber will result in less gas for the process—also in the case of mass flow control—and a lower collision rate. With self-excited electron resonance spectroscopy (SEERS), plasma parameters such as electron collision rate and electron (plasma) density can be measured in real-time.

The SEERS method is based on passive measurement of the RF discharge current by an RF sensor and a physical model of the plasma. These parameters are well-known to plasma physicists but not widely used for production control. The plasma parameters are measured by the plasma metrology system Hercules.

Electron collision rate and electron density have been implemented in the Maestria FDC software, which has been used to detect hardware- and process-related issues over a period of 18 months. Due to the sensitivity of the plasma parameters, the chamber state (conditioning), process drifts, wafer properties, arcing, and process or tool faults can now be detected.

Plasma parameters are closely linked to the actual process and are capable of describing process-relevant chemistry. These parameters are sensitive to 1) tool parameters such as gas flow, pressure, and power; 2) process/chamber drift for conditioning, cleaning, or waferless auto-clean (WAC) issues; 3) different products (e.g., open area and chamber matching); and 4) tool excursions caused by the capacitance manometer, RF, MFC, etc.

SEERS application examples

Example 1: To protect the health and safety of maintenance personnel, a special cleaning procedure is performed before chamber venting. This procedure removes toxic by-products from the chamber wall and consists of nine plasma cycles followed by a pump-purge, and requires two hours. The number of plasma clean cycles was empirically determined. The optimization of the pre-clean procedure before chamber venting was done by correlating the collision rate with the chamber state.

The electron collision rate shows that the main cleaning effect of the chamber occurs during the first cycle of the cleaning procedure. Three to five cycles are sufficient for a stable state before opening the chamber. One hour of pre-cleaning time was saved and tool uptime was increased after implementing the new cleaning procedure; no negative impact on the cleaning efficiency has been observed. Except for the electron collision rate, no other tool parameter is capable of indicating the chemical condition of the chamber.

Example 2: After wet clean, an O_2-process was run followed by 20 conditioning wafers. With the capability to monitor the chamber state, the conditioning procedure after wet clean was optimized. The collision rate clearly shows that the chamber is conditioned (stable) after only five wafers. The reduction to 10 conditioning wafers has already been implemented without any problems. The optimized conditioning procedure saves 50% of the time needed for conditioning as well as 50% of the number of conditioning wafers.

Process and chamber characterization

Sometimes poly and nitride have to be accomplished on the same tool if there is no dedicated etch tool available for nitride and poly (for backup reasons). While the

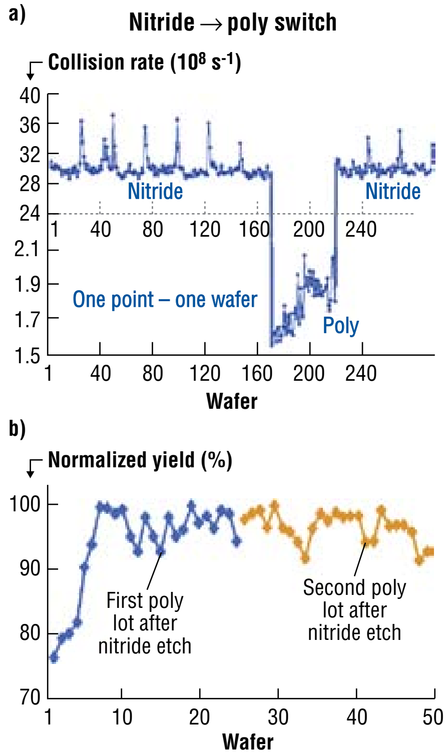

Figure 2. Process instability after product change is yield-related.

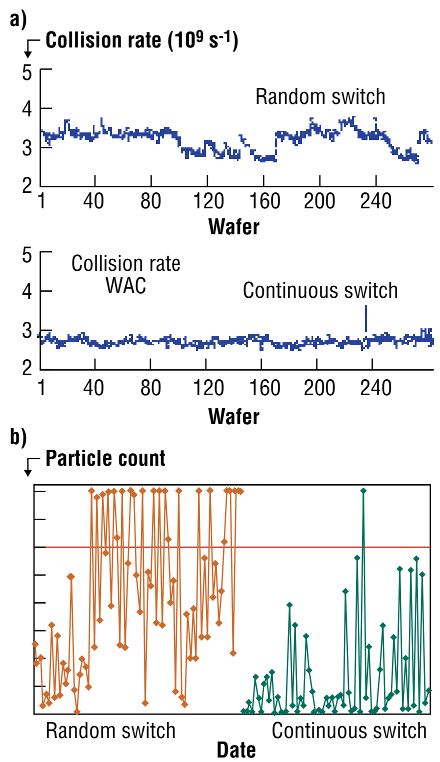

Figure 3. Continuous switch **a)** increases process stability and leads to **b)** less particle generation.

tool parameters indicate process stability, relevant deviations of the etch results were found. Using the plasma parameters, the following questions should be answered: 1) Is the process stable after switching from poly to nitride, and vice versa (**Fig. 2a**)? 2) Is conditioning necessary?, and 3) Is the WAC stable and sufficient?

The switch between poly and nitride etch means a change between fluorine- and chlorine-based chemistries, which can cause yield loss due to particles falling from the top plate (**Fig. 2b**). Continuous switching between etching nitride and poly layers stabilizes the processes without additional conditioning (**Fig. 3a**). An increase in mean-time-between-cleans (MTBC) could therefore be possible.

Improving MTBC and particle performance by continuously switching (**Fig. 3b**) between poly and nitride is not new to us. Several years ago, a similar problem appeared on another etch tool in terms of particle counts, and that was solved by continuous switching. With plasma parameters such as electron collision rate, variations inside the chamber can now be controlled in real-time.

Highly effective FDC

One example that demonstrates the power of plasma parameters in an FDC system is how unstable plasma conditions were detected by the electron collision rate after a maintenance procedure. Within the lots, the collision rate jumped suddenly and remained at a high level afterwards (**Fig. 4a**).

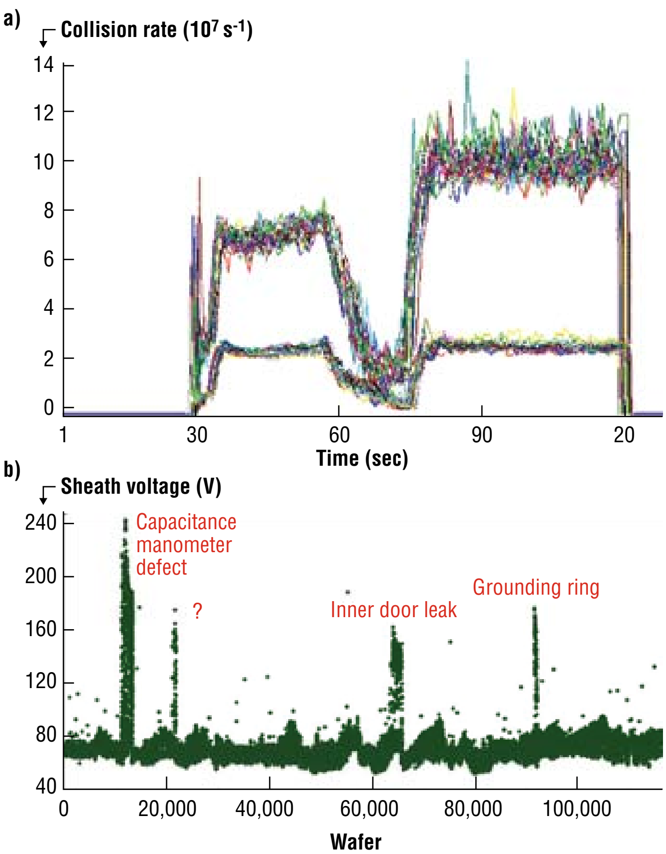

Figure 4. Shift of collision rate **a)** during a lot resulted in two different plasma states for one lot and for **b)** long-term analysis.

As is often the case, the first idea to solve a process stability problem was to exchange the matchbox; however, the collision rate already indicated an issue with either temperature, conditioning, or chemistry. Therefore, the real problem was not solved. Analyzing the data indicated that the wafer ID within the lot where the collision rate jumps is related to the idle time before processing the lot. The longer the idle time, the later the collision rate increased within the lot. During the etch process, the chamber heats up, and when the chamber is idle, it cools down. As already indicated by the electron collision rate, the process issue should be related to a temperature effect. If the chamber parts reach a certain temperature, the plasma switches to an unstable mode, thus altering thermal or electrical conditions.

Taking into account that the process fault occurs after a maintenance procedure, the chamber was re-opened. It was found that the screws of the grounding ring inside the chamber were loose. Due to the thermal coefficient of expansion of this ring, the electrical conditions changed at a certain temperature and led to the increased collision rate. The observed difference of the collision rate was >600%; the peak voltage varied by 6% and the shift of the optical endpoint signal was zero. Without plasma parameters, no maintenance in the world would have been able to detect this problem, as the shift of well-known standard parameters was too small to detect.

Conclusion

New technologies, increased end-user requirements, and limited human resources led to new challenges to process control. Small structures and complex technologies require new methods that provide very sensitive parameters and describe all product-relevant processes because most tool parameters are not able to detect yield-relevant deviations. Plasma parameters such as electron collision rate and electron density address these problems. Implemented in FDC software such as Maestria, the sensitivity of these parameters enables efficient process control. In the last 12 months, four problems on just one etch tool have been detected (**Fig. 4b**). This would not have been possible without the use of plasma parameters.

Plasma parameters are used to reduce costs by increasing uptime, yield, and MTBC. They shorten the time for FDC, process development, optimization, and transfer, and facilitate high-level quality management. Knowledge about plasma parameters has significantly improved the understanding and ability to control plasma processes. During recent years, all the expected application capabilities with SEERS have been verified, and we can presently predict the chamber state and yield relevant process variations. This is an important step to real APC. ■

Acknowledgments

Maestria is a registered trademark of PDF Solutions. Hercules is a registered trademark of Plasmetrex GmbH.

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