WHITE PAPER

Mass Flow Controllers

A New Class of MFCs with Embedded Flow Diagnostics

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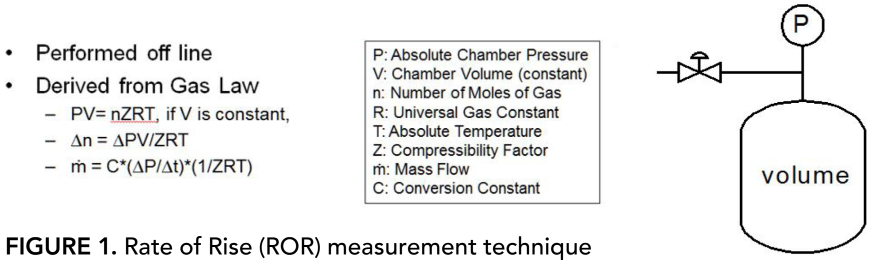
Recent trends in multi-sensor measurements within a mass flow controller are reviewed, with a focus on controller self-diagnostics.

Sub 20nm nodes and complex 3D architecture are driving new process control challenges. In regards to gas delivery, these complex and highly sensitive processes require mass flow controllers (MFCs) to provide better accuracy, repeatability, long term stability and consistent dynamic response. In addition, foundries are driving a need for greater process and equipment flexibility which means the MFC must meet demanding process requirements across a wider control range.

While the quality, reliability, accuracy, response and range of MFCs continues to improve year after year, the process is still at risk because meaningful real-time in situ data is limited or nonexistent. Consequently, an error in delivered flow that is substantial enough to cause yield and scrap issues would go undetected until the next off-line flow check.

In situ data traditionally has been limited to detecting obvious hard failures such as an MFC that is not communicating; the flow output doesn't meet the set point; or the MFC output at a zero set point is offset (not zero). A zero offset will cause a change in flow accuracy if it is due to an active change in the zero reference of the flow meter. However, zero offsets recorded during a process can also be caused by an MFC valve leak or even an isolation valve leak. A few fault detection and clarification (FDC) systems attempt to trend valve voltage but hysteresis of up to 40 percent of a reading means that only obvious failures can be detected.

In lieu of in situ flow data, flow tests are performed off-line using a technique such as chamber rate of rise (ROR). The ROR technique is simply to evacuate a known volume, flow gas into it and measure pressure change. With chamber ROR, the known volume is the processing chamber. The chamber is taken off-line (not running a process) and the MFC is given a flow set point. As gas flows into the constant volume chamber, the chamber pressure rises at a constant rate. Flow can be calculated using the gas law as shown in **FIGURE 1**. Off-line testing reduces tool availability and can only detect flow errors after the fact, placing wafer lots at risk. Chamber ROR accuracy is +/- 3 percent of reading to +/- 5 percent of reading, depending on flow rate, gas properties, temperature gradients, manometer accuracy and chamber outgassing. Even if a better flow standard is available, flow tests are time-consuming. Chamber ROR testing every MFC at only one set point on a four-chamber etch tool can take 12 hours and is typically performed weekly.



- Performed off line
- Derived from Gas Law
    - $PV = nZRT$, if V is constant,
    - $\Delta n = \Delta PV/ZRT$
    - $\dot{m} = C^*(\Delta P/\Delta t)^*(1/ZRT)$

P: Absolute Chamber Pressure
V: Chamber Volume (constant)
n: Number of Moles of Gas
R: Universal Gas Constant
T: Absolute Temperature
Z: Compressibility Factor
$\dot{m}$: Mass Flow
C: Conversion Constant

FIGURE 1. Rate of Rise (ROR) measurement technique

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Process engineers are seeking an in situ flow verification process to ensure process repeatability enabling real-time FDC to alarm on conditions that could lead to wafer scrap. In situ flow data could also be used to intelligently determine when to take a tool down for flow verification tests instead of running time-consuming weekly flow maintenance checks on all MFCs.

The evolution of the MFC

In 2004, MFC manufacturers developed pressure transient insensitive (PTI) MFCs. Pressure sensors were added to measure fluctuations in pressure and advanced control concepts were introduced to compensate for pressure fluctuations in real time.

Recently, several manufacturers have experimented with using pressure and temperature signals available in PTI MFCs to determine if the controller accuracy is degrading. (The authors have used the phrase "multi-sensor diagnostics" to describe this new class of advanced MFCs). Every multi-sensor diagnostic technique involves some form of pressure rate of decay (ROD). ROD is similar to chamber ROR exe. Chcept instead of flowing into a constant volume and measuring the pressure rise, flow is released from a constant volume and the rate of pressure decay is measured. The concept has been around for 30 years and involves shutting off an upstream valve to create a constant volume and measuring the pressure drop within the volume. The technique wasn't practical until digital processors with enough computational power were available to perform the technique.

Multi-sensor diagnostic instrumentation can be broken into two groups. The first group (idle self-diagnostic) can only perform self-diagnostics while the tool is idle or in between process steps. Pressure decay in the volume is measured but there is no attempt to control flow. The signature of the pressure drop is compared to a previous measurement and analyzed to look for changes. While considered an improvement, this technique does not provide true in situ data and a dynamic event during a process could easily go undetected. The second group (active self-diagnostic) actively controls process steps while the pressure decay is measured. Although more challenging to implement, this technique enables true in situ flow verification **(FIGURE 2)**.

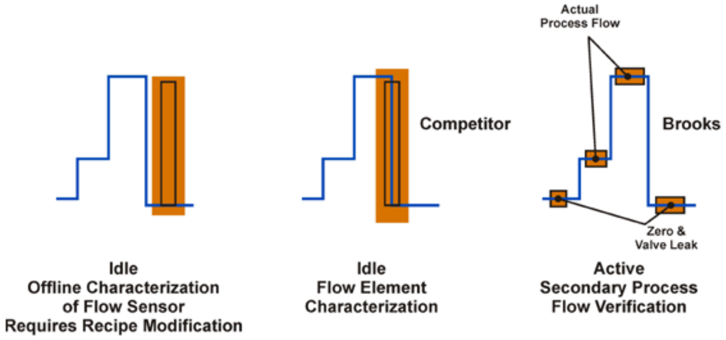


FIGURE 2. Comparison of idle and active self-diagnostic during wafer processing.

Examples of idle self-diagnostics

Example 1 - thermal MFC: The upstream isolation valve is closed and the position of the flow control valve is frozen. The MFC then records pressure decay. The characteristics of the pressure decay curve are compared to a baseline curvanges in the curve are trended to determine if a flow sensor is degrading **(FIGURE 3)**. Special maintenance checks would have to be programed into the tool controller to take advantage of this technique as it cannot be triggered during a normal process run.

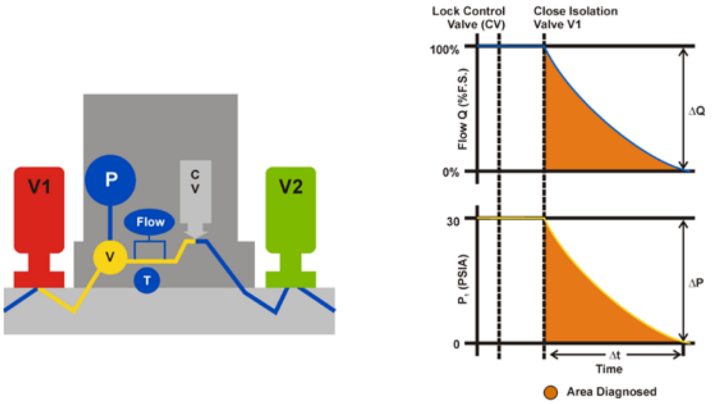


FIGURE 3. Thermal MFC Idle self-diagnostics.

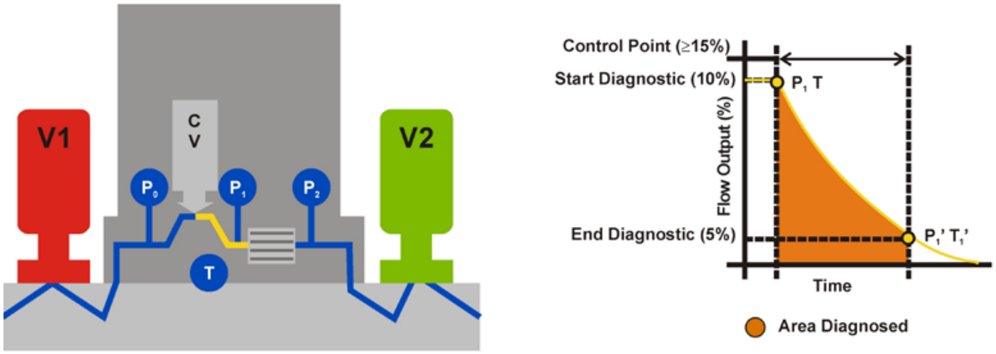


FIGURE 4. Pressure-based MFC idle self-diagnostics

Example 2 - pressure-based MFC: Traditional pressure-based MFCs measure pressure drop across a laminar flow element (LFE) (FIGURE 4). The valve must be placed upstream for two reasons. First, the pressure measurement is more accurate and stable if P2 is vacuum; second, this method requires a stable inlet pressure, P1. The downside to placing the valve upstream is slow turn off. The gas must bleed through the laminar flow element after the gas is turned off. The bleed downtime is a function of gas properties, the laminar flow element volume upstream of the LFE, and pressure in the upstream volume. For multi-sensor diagnostics, the manufacturer takes advantage of the bleed-down and characterizes the pressure decay every time the MFC is given a command to shut off. Any deviation from baseline signifies a change in either the LFE flow path or pressure sensors, and would trigger the user to perform a maintenance check.

Active self-diagnostics

Unlike idle self-diagnostics, where MFC characterization is performed when the MFC is not running a process, the latest development in multi-sensor self-diagnostics enables true in situ flow verification. This means flow anomalies can be captured in real-time during a process and assessed before several wafers are affected.

FIGURE 5 shows the cross-section of a multi-sensor self-diagnostic MFC mounted on a traditional surface mount gas stick. In this example, the MFC contains a pilot valve that enables the MFC to control the state of the upstream isolation valve. Other implementations integrate the isolation valve into the body of the MFC.

The MFC closes the upstream isolation valve when it is ready to take a secondary flow measurement. This creates a fixed volume between the isolation valve and the MFC control valve. While pressure decays in the volume, the MFC control system continues to maintain flow while recording pressure, temperature and time. A secondary flow measurement is computed based on the pressure decay (ROD) and compared to baseline data recorded during the installation of the MFC on the tool. Once this measurement is complete, the MFC re-opens the isolation valve. PTI technology is used to compensate for the initial pressure spike, ensuring continued stable flow. The same measurement technique can be used to monitor zero drift and valve leak when the MFC is given a zero set point.

Case study on etch process tool at leading IDM

Two multi-sensor MFCs capable of active self-diagnostics were installed on an etch chamber at a major integrated device manufacturer. The MFCs were configured to store accuracy, zero drift and valve leak self-diagnostic data in flash memory located within the MFC. Performance transparency tests were run with self-diagnostics activated to ensure the technology did not change the process.

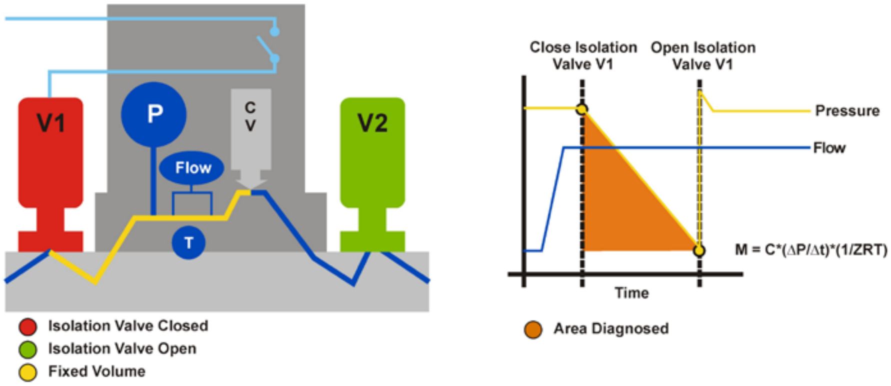
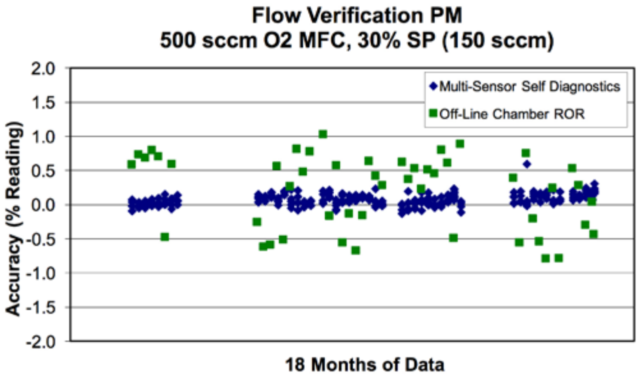


FIGURE 5. Thermal MFC active self-diagnostics.



Chamber ROR Technique
Measurement Resolution: ±1.6% SP
Tool Downtime: >10 hours

GF135 Multi-Sensor Diagnostics
Measurement Resolution: ±0.2% SP
Tool Downtime: 0 hours

FIGURE 6. Chamber ROR flow verification vs. multi-sensor self-diagnostics.

The process engineers continued to perform regular off-line flow verification tests at a set point of 30 percent. No accuracy issues were detected by the traditional maintenance tests and no adjustments such as re-zeroing or re-calibration were performed. Data was collected for 24 months.

Active multi-sensor diagnostics vs. off-line chamber ROR: Self-diagnostic data was collected during the regular off-line flow verification tests. **FIGURE 6** shows that repeatability of self-diagnostics was 8X better than the time-consuming off-line flow verification tests.

Active flow accuracy: The etch process utilized MFC set points of 4 percent, 12 percent, 24 percent and 40 percent **(FIGURE 7)**. In situ active self-diagnostic data was automatically collected at each set point every three seconds during wafer processing. The MFC flow accuracy was very repeatable over the two-year test period at set points of 24 percent and 40 percent.

However, flow accuracy at 4 percent shows an increase in flow of 1 percent over the two-year evaluation period. Note that off-line flow verification tests were only performed at a set point of 30 percent where the MFC is stable. Traditional off-line chamber ROR flow tests proved not only to be costly, but also ineffective in detecting flow changes in this case.

In situ zero drift trending: Increasing flow errors at low set points usually indicate a change in the zero of the flow meter. The output of a flow meter should be zero at no flow. However, all measurement instruments will eventually drift resulting in some level of zero offset. A small zero offset in the flow meter is a negligible part of the flow signal at a high flow rate.

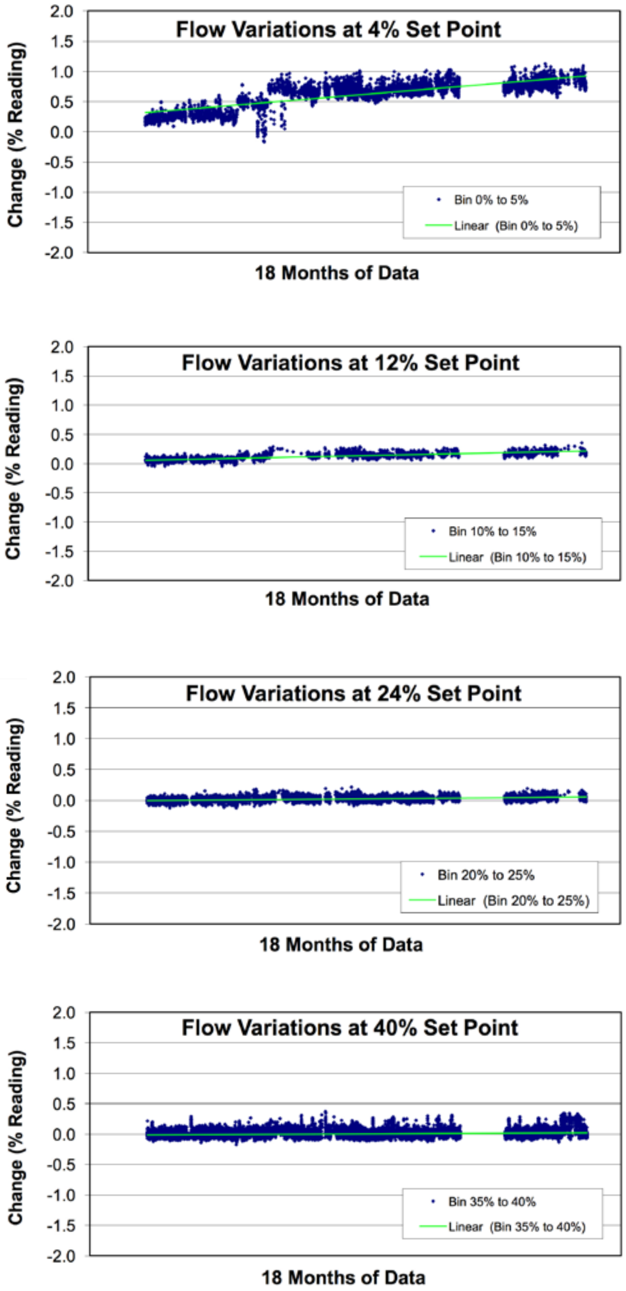


FIGURE 7. In situ flow accuracy results.

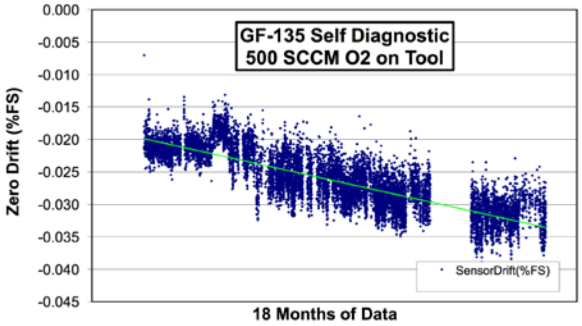


FIGURE 8. In situ zero trending results (20x magnification)

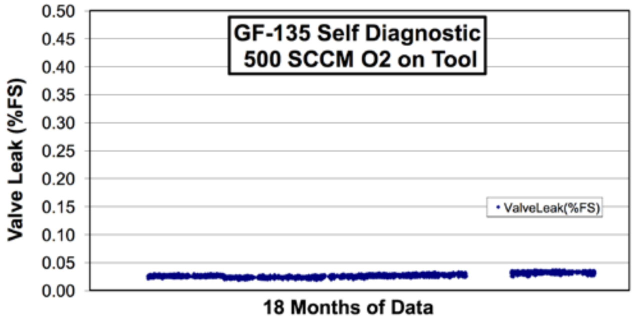


FIGURE 9. In situ valve leak results.

	Flow-Related Process Data Available to FDC System			
Data Type	**Traditional MFC In Situ Data**	**Tool Off-line**	**MFC w/ Idle Self-Diagnostics**	**MFC w/ Active Self-Diagnostics**
MFC Output	+/- 0.05 % SP		+/- 0.05 %	+/- 0.05 %
Temperature	+/- 1 °C		+/- 1 °C	+/- 1 °C
Inlet Pressure	+/- 0.1 PSI		+/- 0.1 PSI	+/- 0.1 PSI
Valve Voltage	Varies +/- 20%		Varies +/- 20%	Varies +/- 20%
MFC Zero		+/- 0.05 %F		+/- 0.02 %F
MFC Valve Leak		0.05 %FS		0.02 %FS
Changes in Flow Accuracy		+/- 3 %SP	TBD	+/- 0.3 %SP
Detects Flow Deviations During Wafer Process				Yes

TABLE 1.

However, small zero offsets can become significant when the MFC is operated at low set point such as 4 percent shown in this tool data. Consequently, the self-diagnostic zero reading was analyzed to see if the accuracy error at a 4 percent set point correlated with zero drift.

The MFC zero drift rate was < 0.027 percent full scale (FS) per year. This is exceptionally stable and 20X less than the spec limit **(FIGURE 8)**. No maintenance test performed today on-tool would identify this low level of zero drift. This data highlights recent improvements in the stability of thermal MFCs. However, expanding the zero drift axis does reveal a slight trend in zero of 0.045 percent FS. This offset is exactly equal to the 1.1 percent of reading flow error identified during process runs at the 4 percent set point

Valve leak: Valve leak is linked to first wafer effects and can indicate contamination in the gas delivery line. Excessive valve leak can cause loss of control at low set points. Self-diagnostic valve leak was trended during this study.

The MFC valve leak was extremely low and stable throughout the study **(FIGURE 9)**. Process engineers typically get concerned when valve leak reaches 0.5 percent FS to 1.0 percent FS. The data reveals excellent resolution of the valve measurement

and demonstrates how easy it would be to detect changes in valve leak well before it could affect process yield.

TABLE 1 compares data and resolution available in situ from a traditional MFC; a tool in idle mode; a tool off-line; and the active multi-sensor self-diagnostic data captured in this study. The process knowledge gained from this technology enables the process engineer to be proactive instead of reactive. In addition, an intelligent FDC system could use this data to identify more subtle MFC issues such as excessive sensitivity to changes in pressure or temperature, and even leaks in the gas stick isolation valves

Conclusions

This data highlights how current best known methods for MFC on-tool monitoring and off-line maintenance are unable to capture changes in process and ensure repeatability.

The on-tool study demonstrated multi-sensor self-diagnostic MFC technology is a process-transparent upgrade with the capability to:

- Track flow changes in situ with 10X better resolution than currently available for off-line flow verification processes
- Enable advanced fault detection and classification where MFC performance is tracked while running process, and logic trees can be set up to determine root causes of process degradation
- Increase tool up-time, where determining the root cause before taking the tool off-line will minimize downtime; reduce or eliminate scheduled flow-verification tests; reduce troubleshooting; and reduce tool maintenance
- Eliminate MFC-induced wafer scrap, using an alarm to alert for conditions that may lead to wafer scrap before producing product.

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