A New Device for Highly Accurate Gas Flow Control With Extremely Fast Response Times

Kevin Boyd*, Adam Monkowski†, Jialing Chen†, Tao Ding†, Ray Malone† and Joseph Monkowski†
*IBM Corporation
Hopewell Junction, New York
†Pivotal Systems Corporation
4683 Chabot Drive Pleasanton, California 94588

***Abstract*—This paper presents a new type of control scheme and device for controlling gas flow into semiconductor process chambers. The key component of the Gas Flow Controller (GFC) is a high-precision valve with an integrated position sensor, which is used to maintain a constant flow rate. A map lookup scheme is employed to adjust the valve position to accommodate the upstream pressure, including any changes or disturbances. The layout of the flow controller also allows for the incorporation of a pressure-volume-time-temperature-based flow measurement, which is a primary standard flow measurement, to confirm and maintain flow accuracy throughout the device's lifetime. The fast response time of the sensors and the high sampling rate in the control loop enables the control of the gas flow within the order of tens of milliseconds.**

I. INTRODUCTION

In plasma-etch and chemical vapor deposition processes, accurate metering of gas flow into the process chamber is critical because, beyond the process wafer, all materials that participate in the etch or deposition are introduced in gas form. In a majority of these processes, two or more of these gases react to produce the essential film or passivation layer and even slight deviations in gas flow—even on the order of 1%—can cause the process to fail. While numerous technologies have been developed to accomplish gas flow metering, the semiconductor market has focused largely on two: the thermal-based mass flow controller (MFC) and the more recently introduced pressure-based flow controller.

These two technologies have served the industry well for a number of years; however, as critical dimensions continue to decrease, process envelopes become tighter, and process steps become shorter, these technologies are reaching their limit. For the semiconductor industry, an ideal gas flow control device will respond instantly ($\ll 1$ sec) with no overshoot, and will produce a flow that is accurate and does not drift over time. Further, flow accuracy will be maintained in the presence of significant (up to several hundred Torr) downstream pressure and will remain accurate in the presence of fluctuations in supply pressure.

Figure 1 shows the basic control loops present in thermal and pressure-based flow controllers. Thermal MFCs rely on a flow sensor, shown in Fig. 1-A, that was developed by Benson, et al., in the 1960s [1]–[3]. Since its development, the thermal flow sensor has been widely applied across many industries and it has been improved to be less sensitive to attitude and temperature variation. The thermal flow sensor works on the principle of heating and cooling a temperature sensor (usually a wound metallic element), and the flow sensor's response time is a function of both the heat capacity of the temperature sensor and the quality of its thermal communication with the gas. For ultra-high-purity (UHP) applications, where the gas cannot be in direct contact with the temperature sensor, the response time is on the order of 1 sec [4]. This represents an inherent limit to the response time for thermal-based MFCs. To circumvent this limit, some thermal-based MFC designs rely on an open-loop control scheme at turn-on, but since the flow sensor cannot measure quickly enough, overshoot and oscillation in flow can occur without being detected by the flow sensor.

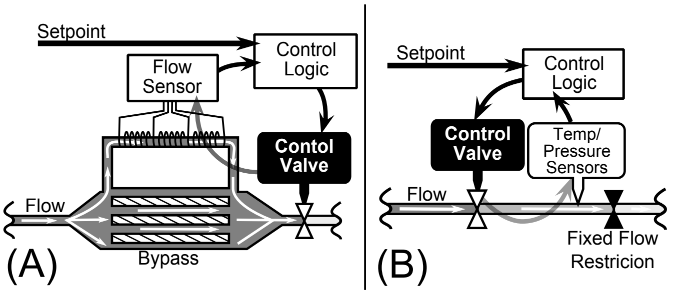

Figure 1. Schematic of flow control schemes for mass flow controllers used in the semiconductor manufacturing industry. A) Thermal Mass Flowmeter: A thermal flow sensor passes data to the control logic which adjusts a control valve to minimize the difference between the flow sensor feedback and an external setpoint. B) Pressure-based flow controller: The relationship between flow rate through the fixed flow restriction and gas pressure is known. The control logic brings the pressure to the required level, based on the external setpoint.

In contrast, the pressure-based flow controller relies on a pressure transducer as its primary feedback sensor. Flow is controlled by varying the pressure upstream of a calibrated flow restriction. The pressure sensor can have a response time of < 1 ms, allowing for fast measurement of flow. Turn-on time for the pressure-based flow controller is governed by how quickly the volume between the control valve and calibrated flow restriction can be pressurized (see Fig. 1-B). Generally, the turn-on time of a pressure-based flow controller is similar to the thermal MFC. Additionally, pressure-based flow controllers are less sensitive to upstream pressure variations, due to the fast response time of the pressure sensor; however, they are more sensitive to downstream pressure fluctuations, as they can possibly change the assumed pressure-to-flow relationship of the calibrated flow restriction. Additionally, since the valve that controls flow is upstream of the pressure-controlled volume, for turn-off or turn-down, the response time of the pressure-based flow controller is limited by the time it takes for the gas in the pressure-controlled volume to be evacuated through the calibrated flow restriction and into the process chamber. This time can be on the order of several seconds for some devices.

To overcome some of the limitations present in the two designs, Pivotal Systems has proposed a new type of gas flow control device which is focused on improving response time and long-term accuracy. In Pivotal's gas flow controller (GFC$^{\text{TM}}$), there are two independent control systems for measuring and controlling flow. The primary system is a fast, map-based valve control system that allows the device to respond rapidly to changes in setpoint and upstream pressure. The secondary system, named Gas Flow Monitor (GFM$^{\text{TM}}$), measures the flow of the GFC using a pressure-rate-of-change flow measurement. This secondary system does not operate as rapidly as the primary system; it is used to validate and if necessary, update, the control map.

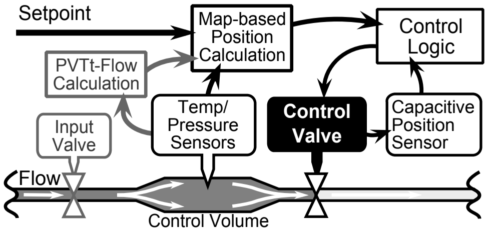

Figure 2. Schematic of flow control schemes for the Pivotal Gas Flow Controller. A capacitive position sensor measures the position of the control valve. Based on the pressure, temperature, and external setpoint input, a position is calculated, and the control logic drives the control valve to move to the desired position. Additionally, an input valve can be closed and the pressure and temperature data can be used to calculate the absolute flow rate through the control valve.

A. Gas Flow Monitor Approach

A real-time in-situ GFM system [5] is incorporated in the GFC to measure flow. The measurement is based on pressure–rate-of-change, in which a total of four independent variables are considered: pressure (P), volume (V), temperature (T), and time (t). The benefit of the pressure-volume-temperature-time (PVTt) type of measurement is that it is a primary standard flow measurement, that is, one that relies only on fundamental state variables and time [6], [7]. The GFM's measurement is performed on the gas in an isolated volume between the control valve and the input valve as shown in Fig. 2. This volume is calibrated and assumed to be constant for all time. GFM monitors pressure and temperature data as a function of time to determine the rate of change of gas density in the volume. A flow rate out of the volume is then established using an appropriate equation of state—typically either the ideal gas law or the Virial equation of state.

A potential pitfall to the application of a PVTt primary flow measurement such as this, in which volume is held constant and pressure is dynamic, is that adiabatic cooling of the gas must be considered. However, with careful design of the calibrated volume such that the volume primarily consists of passages approximately 0.180" or less in diameter (a typical passage diameter for UHP flow designs), or a geometry with similar sized passages, the deviation of the average temperature of the gas from the stainless steel body is $< 0.1\%$ on an absolute scale. This estimation of the gas temperature from that of the stainless steel body, combined with accurate volume and pressure data, is able to yield very accurate flow measurements.

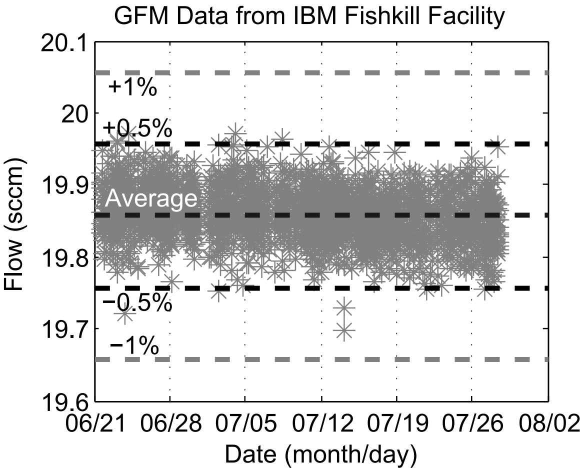

Figure 3. Plot of GFM data on a production plasma oxide etch tool at IBM's Fishkill facility. Each point represents the GFM measurement taken at the beginning of an individual flow run. 1%, and 0.5% deviation bars are shown with respect to the average flow rate observed; the MFC flow setpoint was 20 sccm.

This gas flow measurement method has been tested and implemented in several major chip makers' R&D labs and manufacturing fabs on both thermal-based and pressure-based flow controllers. Figure 3 shows one month's worth of data taken from a GFM running in high-volume production at IBM's Fishkill facility. In this application the GFM measures the gas flow for each process run and shows the variability of the MFC's flow rate over time. Figure 4 shows accuracy tests conducted on the GFM comparing it to a DH Instruments Molbloc$^{\text{TM}}$system, measuring the steady flow from a thermal MFC (100 sccm full scale) at different flow setpoints. The measurements from the GFM show excellent correlation with the Molbloc system.

B. Gas Flow Controller Approach

The control scheme for the GFC is shown in Fig. 2. The primary control system consists of a precision position sensor coupled with a control valve such that when the valve is closed the position sensor output is zero and as the valve is opened the

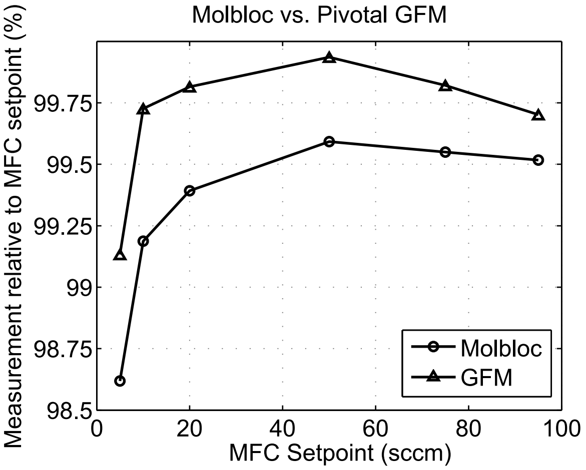

Figure 4. Pivotal GFM measurements compared to Molbloc™ measurements (stated accuracy: 0.2%) on a 100 sccm MFC flowing various flow rates. GFM measurements are within 0.5% of the Molbloc across the range of flows measured.

sensor determines the opening of the valve in units of length. To produce a constant flow rate, a digital signal processor (DSP) receives three inputs: the setpoint, as well as pressure and temperature data from the the gas in the calibrated volume directly upstream of the control valve. The DSP uses this data to calculate a target position that will produce the desired flow rate using a pre-determined control map. This target position is passed to the valve control loop and the drive voltage to the control valve is adjusted so that the output of the position sensor matches the target. A flow rate feedback signal (GFC feedback) is generated in a similar fashion; data from the position sensor, along with pressure and temperature data is passed to the DSP, and using the same control map, a flow rate is calculated that corresponds to the present valve position.

The position sensor is based on a capacitance measurement. This type of capacitive position sensor has a response time $< 1{\times}10^{-3}$ sec; therefore, the control loop can be run at speeds over 1000 Hz. The piezoelectric element that drives the valve also has a response time $\ll 1{\times}10^{-3}$ sec. The desired flow rate can be reached as quickly as the control logic can bring the valve to the desired position; this time can be on the order of milliseconds. This rapid response produces a flow controller that can be turned on or turned down in terms of milliseconds, and is insensitive to sudden changes in upstream pressure. Changes in pressure will simply result in a new target position for the control valve.

This inherent pressure insensitivity allows the GFC to be run with the secondary flow measurement system, GFM, directly upstream of the control valve. In brief, the measurement is taken by closing an input valve to isolate the calibrated volume (V_{cal}) directly upstream of the control valve. This configuration is shown in Fig. 2. As the pressure in V_{cal} drops, the control valve responds by adjusting its position accordingly per changing pressure, while the GFM uses the pressure data to calculate an independent flow measurement. When the GFM's measurements are complete, the input valve is opened and flow continues normally with the control valve responding to the pressure increase.

The GFM behavior can be configured in several different ways. After the input valve is closed, an accurate GFM measurement can be calculated within a pressure drop of < 1 psi; however, if the pressure is allowed to decrease further, additional GFM measurements are continually calculated until a low pressure limit is reached. These GFM measurements are compared, real-time, with the flow rates calculated by the primary control loop to verify correct operation. The GFM can be configured to run once at the beginning of each flow run, or multiple times throughout the run.

II. TEST SETUP

A test bench, as depicted in Fig. 5, is set up to show both the steady state and transient state of the Pivotal GFC control results. The bench consists of a standard 1-1/8 inch C-seal gas stick, one pressure regulator (set at 27 psig), one Pivotal GFC (200 sccm full scale), one pressure gauge (MKS baratron type; 1000 Torr full scale), one thermal mass flow meter (MFM) and one vacuum pump downstream of the gas stick (pressure < 100 Torr) . The pressure transducer is installed between the GFC and MFM to ensure the steady flow. In other words, if the gauge shows a constant pressure during the flow, the flow through the MFM is equal to the flow out of Pivotal GFC. The DSP is running at 1040 Hz for the following tests.

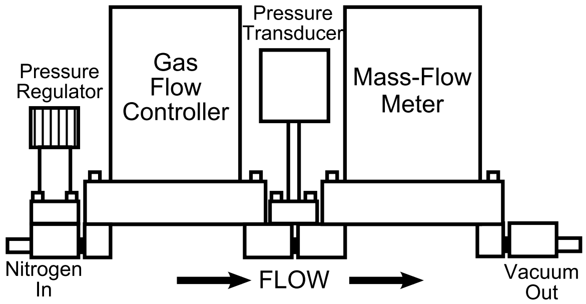

Figure 5. Schematic of the configuration used for GFC testing. The mass flow meter (MFM) has a full scale range of 100 sccm.

The GFC's control valve shown in Fig. 2 is a normally closed flow restriction that is actuated with a piezoelectric element. The capacitive position sensor is mechanically coupled to the flow restriction, such that any movement at the flow restriction results in a linearly proportional response from the position sensor.

A. Response Time

Figure 6 shows how the GFC responds to a setpoint change. Twelve individual runs have been overlaid, with a characteristic response trace highlighted to show the trend; the individual feedback points generated by the DSP are represented in crosses. At time zero, the flow command changed from 0 to 20 sccm; the GFC starts to respond to the command at

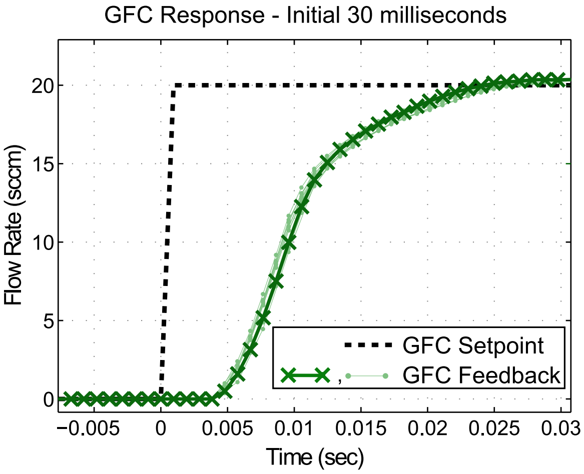

Figure 6. Plot showing the response of the GFC primary control loop to a setpoint change from 0 to 20 sccm. Twelve individual tests are overlaid; a characteristic response has been highlighted.

time 4 msec and its control settling times for all of these 12 trials were about 30 msec. The logic used to drive the valve is a standard proportional-integral (PI), closed loop type. The fast response of the system allows the use of conservative P and I terms that result in over-damped dynamics. As the valve position approaches the target, the changes to the drive signal become smaller and smaller such that overshoot is eliminated.The use of conservative P and I values mean that setpoint is not reached as fast as possible, but because of the speed of the system and its sensors, this can still be accomplished in only tens of milliseconds.

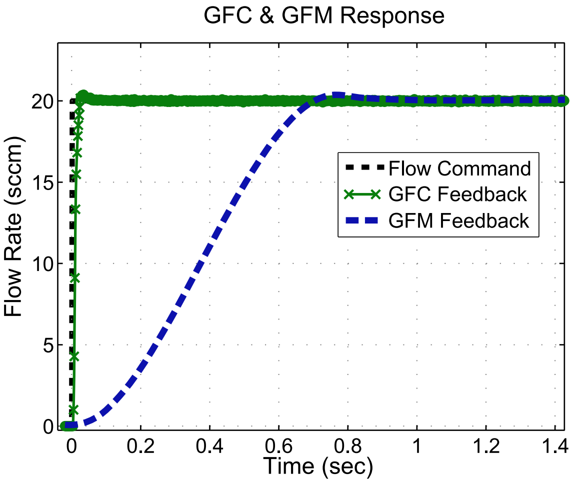

Figure 7. The dynamic response of the gas flow monitor system (GFM), a PVTt, pressure rate-of-change measurement. The response of the primary control valve, GFC (see Fig. 6), is also shown. The response time of the GFM depends on the time over which data is accumulated to calculate a flow rate, in this case, 0.8 second of data is used resulting in a 0.8 sec response time.

B. PVTt Measurement Verification

As described in the previous section, a built-in GFM system is used for the flow verification and calibration. To generate the data shown in Fig. 7, the input valve is closed prior to setpoint change. GFM measurements occur continuously as long as the input valve is closed. In this test, the GFM flow calculation window was set at 0.8 sec; in other words, at each DSP cycle, the most recent 0.8 second of pressure and temperature data are used to calculate the flow through the control valve. This time is not fixed; generally, a GFM calculation uses between 0.05 and 2.0 seconds of data to calculate a flow rate. The amount of data used is primarily a function of flow rate and desired accuracy; higher flow rates can be accurately determined in a shorter time period. As shown in Fig. 7, the GFC was set to flow 20 sccm at time 0, and while the GFC valve took only $\sim$ 30 msec to reach the setpoint, the GFM flow calculation took $\sim$ 0.8 sec to show the true flow change.

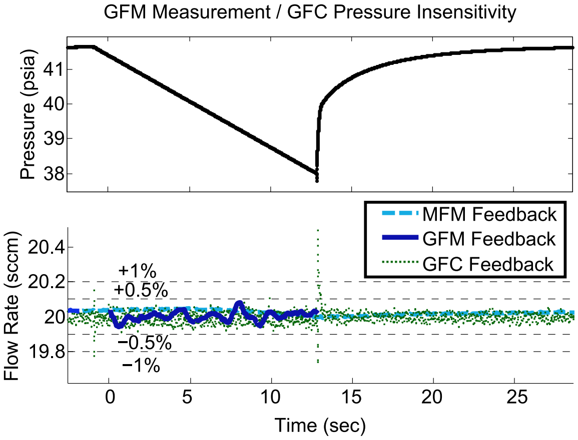

Figure 8. Plot of the combined GFC and GFM feedback signals. The GFM only calculates flow while the input valve is closed. After a measurement is taken, the input valve opens and the pressure increases. The GFC control valve responds to this rapid pressure increase (in this case 10 psi/sec). To verify that flow is not disturbed, a MFM is used to be a third independent measurement; there is no deviation in the MFM output during recharge.

C. Pressure Insensitivity

Figure 8 shows typical steady state behavior of the GFC. At time zero, a GFM measurement is initiated by closing the input valve. The pressure in V_{cal} is shown in the top plot. When the input valve is closed, the pressure starts to decrease from its initial value of 41 psia and continues to drop for $\sim$ 13 sec, to 38 psia. The GFM continually returns flow rate calculations during this time using a rolling window of data points for its calculation. At $t = 13$ sec, the input valve is opened and the pressure in the volume rises back to 41 psia. The initial pressure rise is very fast, approximately 10 psia/sec; however, the control valve is capable of adjusting its position quickly enough to maintain a constant flow rate. For this test, the feedback of the downstream MFM is also shown to corroborate the constancy of flow during this input pressure variation.

III. CONCLUSION

Accurate control of gas flow is critical in semiconductor processing. We have presented a device that incorporates a primary flow standard measurement with a novel control valve that is capable of fast response times. The primary valve control system is map-based and relies on a pressure transducer and capacitance position sensor, both of which have response times on the order of milliseconds. The secondary system verifies the first with a built in primary flow standard measurement systems that uses a PVTt, pressure rate-of-change measurement. The combination of these two systems yeilds a new approach to flow control that offers the semiconductor industry new solutions to difficult gas flow control challenges.

REFERENCES

[1] J. M. Benson, "Benson thermal flowmeter," U.S. Patent 3,181,357, May 4, 1965.

[2] ——, "Thermal flowmeter," U.S. Patent 3,229,522, January 18, 1966.

[3] C. E. Hawk and W. C. Baker, "Measuring small gas flows into vacuum systems," *J. Vac. Sci. Technol.*, vol. 6, no. 1, pp. 255–257, 1969.

[4] L. D. Hinkle and C. F. Mariano, "Toward understanding the fundamental mechanisms and properties of the thermal mass flow controller," *J. Vac. Sci. Technol., A*, vol. 9, no. 3, pp. 2043–2047, 1991.

[5] S. Yedur, A. Sankaran, R. Malone, R. Reed, M. Venkatesh, J. H. Lee, K. Y. Kim, and S. H. Han, "Real-time gas flow monitoring improves mass flow controller performance understanding in wafer fab," *Solid State Technology*, vol. 54, p. 00, March 2011.

[6] R. F. Berg and S. A. Tison, "Two primary standards for low flows of gases," *Journal of Research of the National Institute of Standards and Technology*, vol. 109, no. 4, p. 435, 2004.

[7] J. D. Wright, A. N. Johnson, and M. R. Moldover, "Design and uncertainty analysis for a PVT-t gas flow standard," *Journal of Research of the National Institute of Standards and Technology*, vol. 108, no. 1, pp. 21–47, 2003.