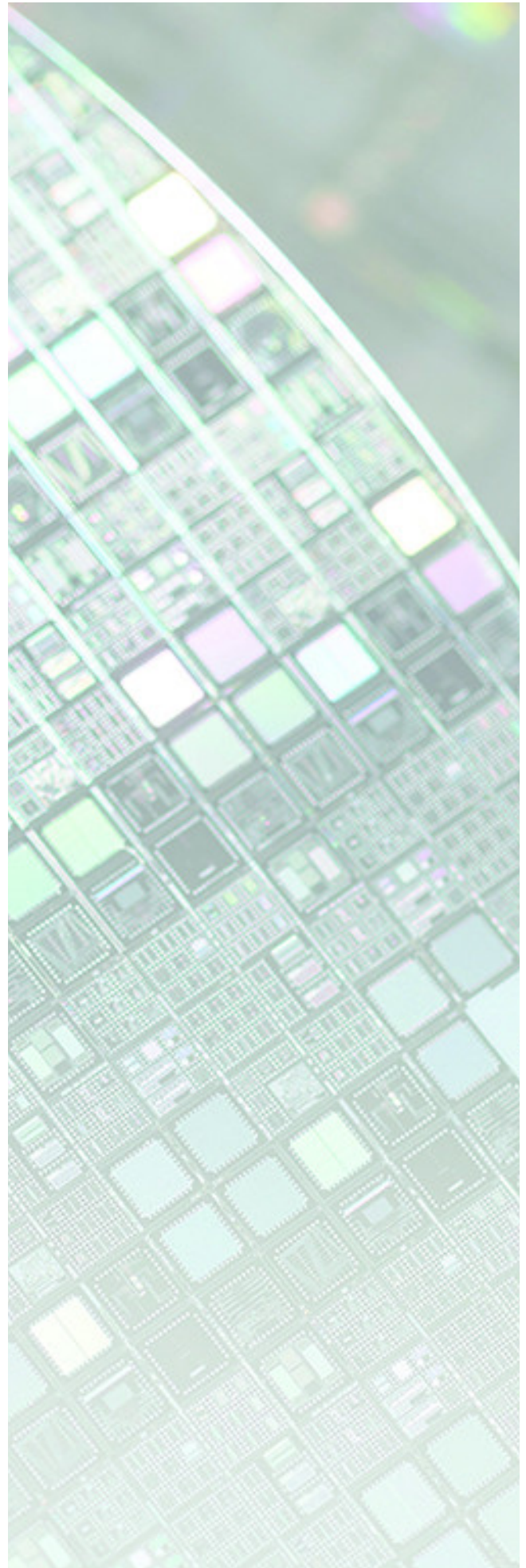


A New Differential Pressure Sensor Based Mass Flow Controller for Advanced Semiconductor Processing

By Mohamed Saleem, Chief Technology Officer, Brooks Instrument



INTRODUCTION: Why Mass Flow Controllers are Important



Mass Flow Controllers (MFCs) are the most critical components of a gas delivery system used for semiconductor manufacturing. Precision gas delivery is at the core of any semiconductor manufacturing. Many different gases- whether corrosive, reactive or inert- are delivered to process chambers in varying flow rates to produce critical features on Silicon wafers that are used in manufacturing logic and memory chips. There is a need to deliver the gases in precise quantities and with excellent repeatability. As the technology transitions to advanced nodes below 10 nm, the requirements for process gas accuracy and repeatability have become of paramount importance. Historically, process gases have been delivered to chambers using either thermal or pressure-based flow controllers. Recently, pressure-based MFCs have been used primarily in critical etch applications as they offer superior flow stability when exposed to upstream pressure transients. They use a defined flow restriction to create a pressure drop in response to the gas flow that is measured and utilize measurements of temperature, upstream absolute pressure and downstream pressure in flow computation. By knowing the fluid properties and flow restriction geometries, classic fluid mechanics principles can be used to determine mass flow rate.

Reduce Measurement Uncertainty with One True Differential Pressure Sensor

Instead of using two absolute pressure sensors to compute pressure drop, a single differential pressure sensor is used. By having an absolute pressure sensor in tandem with a differential pressure sensor, flow can be computed. One significant advantage of this technique is that it eliminates the need for having matched absolute sensors and therefore, **prevents uncontrolled drifts and flow inaccuracies**. In general, differential pressure-based flow measurement yields superior accuracy and repeatability of flow measurement.

Until recently, conventional pressure-based mass flow controllers utilizing absolute pressure transducers and laminar flow or orifice-based flow restrictors have been used for semiconductor processes such as etch, which operate under high vacuum to sub-atmospheric pressure conditions (up to 400 Torr). These MFCs operate well under high vacuum conditions but degrade in performance and control range as the outlet pressures go up. Differential pressure sensor-based MFCs have no such limitations- they operate well in high vacuum conditions at outlet and at above atmospheric pressure conditions (outlet pressure as high as 1200 Torr). This enables extending the use of pressure-based MFCs to semiconductor processes such as chemical vapor deposition (CVD) which in many cases operate at atmospheric or above atmospheric conditions.

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Theory of Differential Pressure-based Mass Flow Controllers

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The performance of a laminar flow element in a mass flow controller is predominantly determined by laminar flow characteristics of the flow restrictor, which can be described by the equation:

$$Q_s = K \cdot (P_{in}^2 - P_d^2) \quad (1)$$

Where:

- Q_s is the mass flow rate;
- K is a value dependent on temperature, viscosity, compressibility of the gas, and the geometry of the laminar flow element;
- P_{in} is the absolute pressure at the inlet upstream of the laminar flow element;
- P_d is the absolute pressure at the outlet (downstream) of the laminar flow element

Disadvantages of Conventional Pressure-based MFCs

Conventional pressure based MFCs utilize two discrete pressure sensors across a laminar flow element to calculate pressure drop, which is used in flow computation. It is imperative that the **two pressure sensors be calibrated and matched precisely** to prevent undesirable drifts in the field [1]. A representative architecture of a conventional pressure-based MFC is shown in Figure 1.

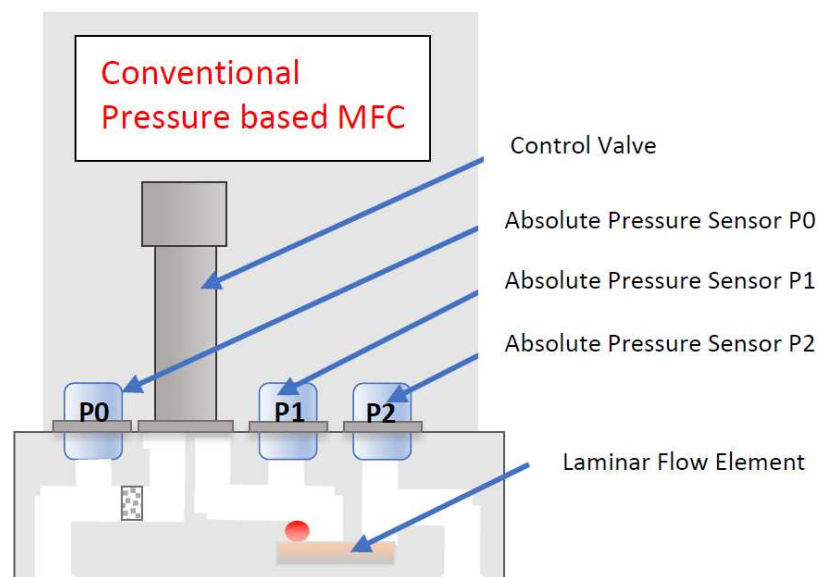


Figure 1. Architecture of a conventional Pressure-based MFC.

In some semiconductor processes such as CVD, the outlet pressure can change from vacuum to more than 760 Torr and this may shift the low-flow pressure drop of the flow sensor by as much as 50X, effectively causing the flow sensor signal-to-noise ratio and the sensor stability to degrade. This will result in **poor repeatability and accuracy** for the operating conditions above “near zero” outlet pressure at low setpoints.

- For example, in conventional MFC designs solving for K for a MFC that has a full-scale N₂ reference flow rate of 100 sccm at P_{in} and P_d pressure values of 360 Torr (7 psia) and 5 Torr (0.1 psia), respectively, provides a K of approximately 2.0412. Using this K, at a 1 sccm N₂ flow and a stated P_d of 5 Torr, P_{in} can be solved to be 36 Torr (0.707 psia), which equates to a pressure difference of 31 Torr (0.607 psia). This pressure difference is well within the resolution limit of typical absolute pressure sensors (~5 Torr or 0.01 psid). Thus, reasonably low error values for the MFC should be obtainable for low setpoint flows when the MFC is operated with a near zero outlet pressure.
- If on the other hand, P_d is increased to approximately 760 Torr (14.7 psia), a typical value that routinely occurs in chemical vapor deposition processes, the corresponding P_{in} required to have a 1 sccm N₂ flow on this same device would equate to approximately 761 Torr (14.7167 psia). This is only a 0.86 Torr (0.0167 psia) difference, which is outside the resolution limit of typical absolute pressure sensors. This inability of conventional pressure-based MFCs to maintain accuracy as outlet pressure is increased is illustrated in Figure 2 (It is assumed in the analysis that absolute pressure sensor is < 0.2% of rate). It shows that as outlet pressure is increased, the measurement error goes up, with the most severe deviations at low flows.

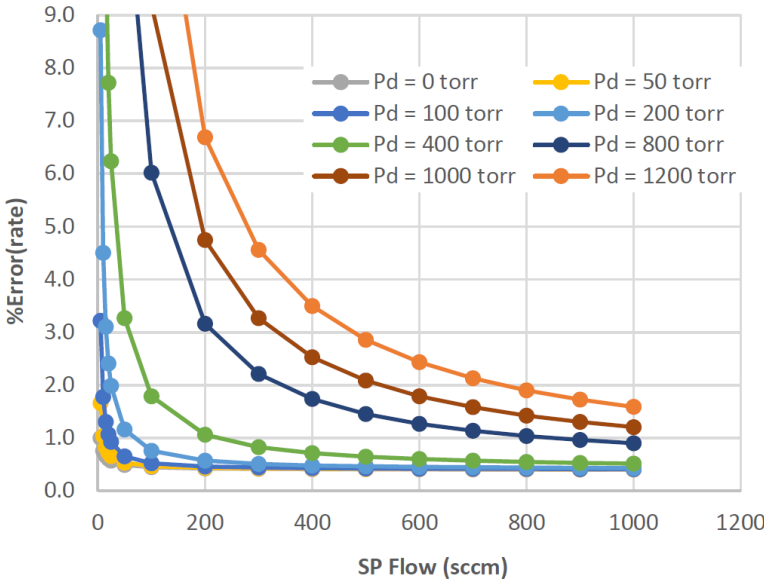


Figure 2. Flow errors in a conventional pressure-based MFC using discrete pressure sensors to measure P_{in} and P_d.

Advantages of a Differential Pressure Sensor-based MFC

In the differential pressure sensor-based MFC described here, absolute flow sensor, a differential pressure sensor and laminar flow element are located upstream of the control valve [2]. Figure 3 depicts the architecture of the MFC. Variations downstream of the control valve will almost always have no impact on the upstream absolute flow sensor. Furthermore, the upstream pressures are typically held to within $\pm 10\%$ of the nominal inlet pressure in a typical semiconductor processing environment [3].

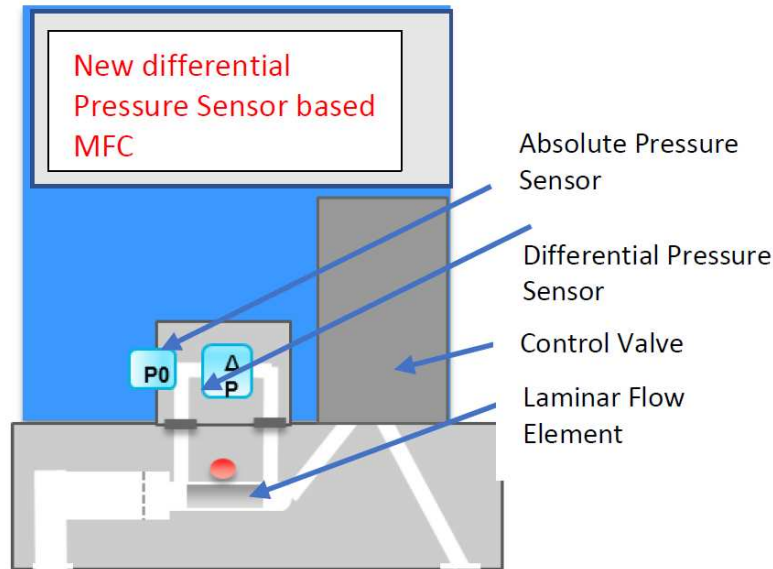


Figure 3. Architecture of a new differential pressure sensor-based MFC.

With the use of a differential pressure sensor in tandem with the absolute pressure sensor, *Equation 1* may now be rewritten as below:

$$Q_s = K^*(2P_{in} - \Delta P)\Delta P \quad (2)$$

Where:

- $\Delta P = P_{in} - P_d$
- Solving *Equation 2* for a 100 sccm N_2 flow at a typical P_{in} of 35 psia (1800 Torr), and a ΔP of 0.86 psid (44 Torr) (allowing reasonable margin for a 1 psid range sensor) at that full-scale flow rate, results in a K of 1.6818. With K known, *Equation 2* may be solved for the at 1 sccm when the P_{in} values are 30, 35, and 40 psia. The resultant values are pressure drops of 0.0099 psid at the 30 psia pressure inlet, 0.0085 psid at the 35 psia pressure inlet, and 0.0074 psid at the 40 psia pressure inlet.

As such, with typical upstream inlet pressure variations, the variation in the differential pressure may be far less with a laminar flow element upstream of the control valve than with a downstream laminar flow element and its associated downstream pressure variations. This is illustrated in Figure 4, where flow errors are plotted vs Set Point flow as a function of inlet pressure (P_{in}). (See next page.)

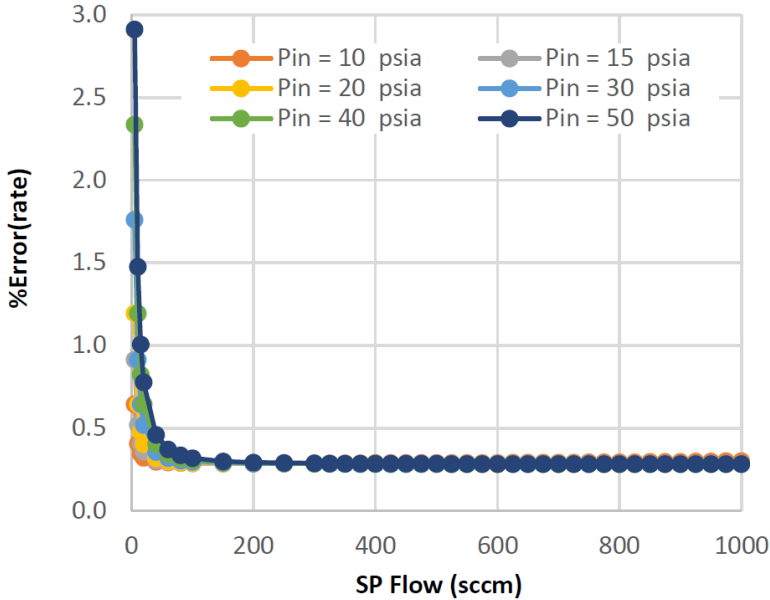


Figure 4. Flow errors in a differential pressure-based MFC showing they are independent of downstream pressures.

Furthermore, differential pressure sensors may be selected with a typical differential pressure accuracy of 0.0005 psid **providing far more accuracy** than currently available with absolute pressure sensors. Thus, the use of a differential pressure sensor in conjunction with an absolute transducer and flow restrictor upstream of the control valve, as opposed to the use of a flow restrictor with two absolute pressure transducers downstream of the control valve, may result in more repeatable flow estimates at desired low setpoints as the inlet pressure varies.

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Evidence-based Results

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The performance of a differential pressure sensor-based MFC has been validated using the test setup shown in Figures 3, 4 and 5. The test setup helps to measure inlet (upstream) and outlet (downstream) pressure insensitivities as well as flow accuracy.

(a) Inlet Pressure Insensitivities

Figure 5 shows the test setup used to evaluate the inlet pressure sensitivity of the MFC. In this test setup, DP MFC is the differential pressure-based MFC (device under test). PR-1 and PR-2 are inlet pressure regulators. V1 and V2 are valves controlling the flow at the inlet of the device under test. Two devices were used for testing, one rated for 500 sccm Nitrogen and other rated for 20,000 sccm Nitrogen. Note that valves V3 and V4 are closed in this test sequence and valve V5 controls flow into vacuum pump (exhaust). The inlet pressure sensitivity can be determined by: (a) With V1 open and V2 closed, giving a set point to the MFC and achieving steady state flow conditions (b) Opening V2 to cause a sudden increase in inlet pressure.

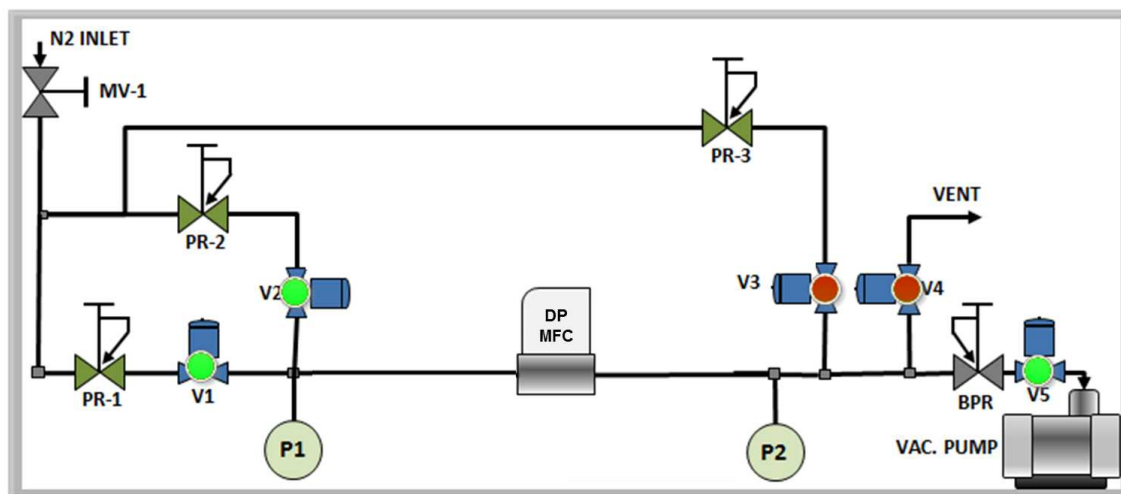


Figure 5: Test setup to evaluate the inlet pressure sensitivity of the differential pressure-based MFC.

Figures 6 and 7 show that for the devices tested (500 sccm N₂ and 20,000 sccm N₂), the MFC flow was unaffected by the rapid change in inlet pressure, even at a severe rate of change in pressure of ~ 30 psi/sec.

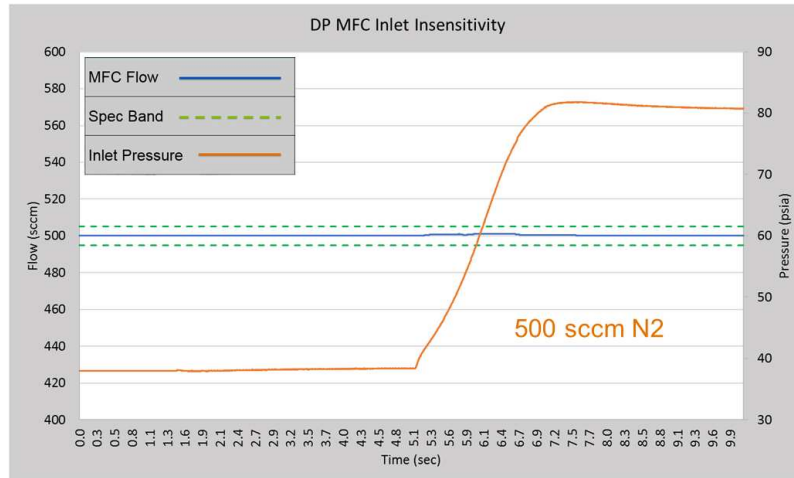


Figure 6: Inlet pressure sensitivity data for 500 sccm Nitrogen device.

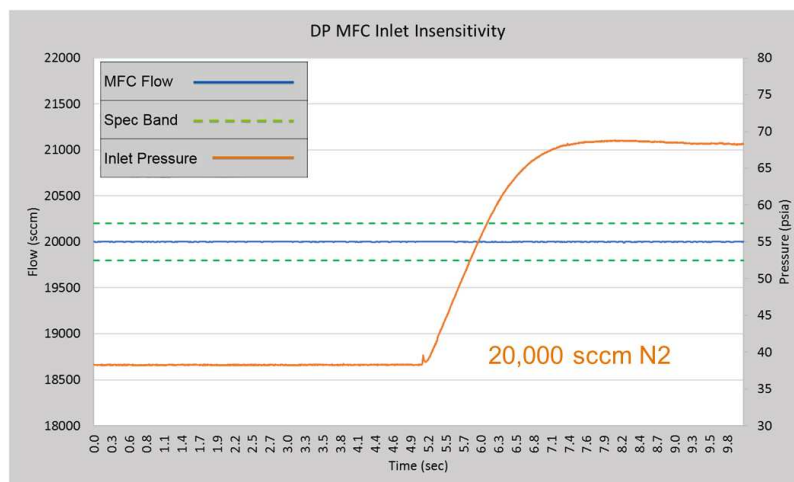


Figure 7: Inlet pressure sensitivity for 20slpm Nitrogen device.

This is typically the extreme change in pressure that can be observed at the inlet to the MFC in a gas panel supplying gases to a process chamber and could be caused by an underperforming inlet regulator or pressure swings caused by another component (e.g., turning off and on) that is manifolded to the gas line tested.

(b) Downstream Pressure Insensitivities

Figure 8 shows the test setup for evaluating the impact of downstream pressure swings on flow in the gas line. This is particularly important for CVD processes where downstream pressure can change from high vacuum to 1100 Torr (~20 psia) depending on the process recipes used. In this test, the outlet pressure is varied from vacuum to 1100 Torr using a back-pressure regulator. Valves V1, V3 and V5 are open and valves V2 and V4 are closed for this test.

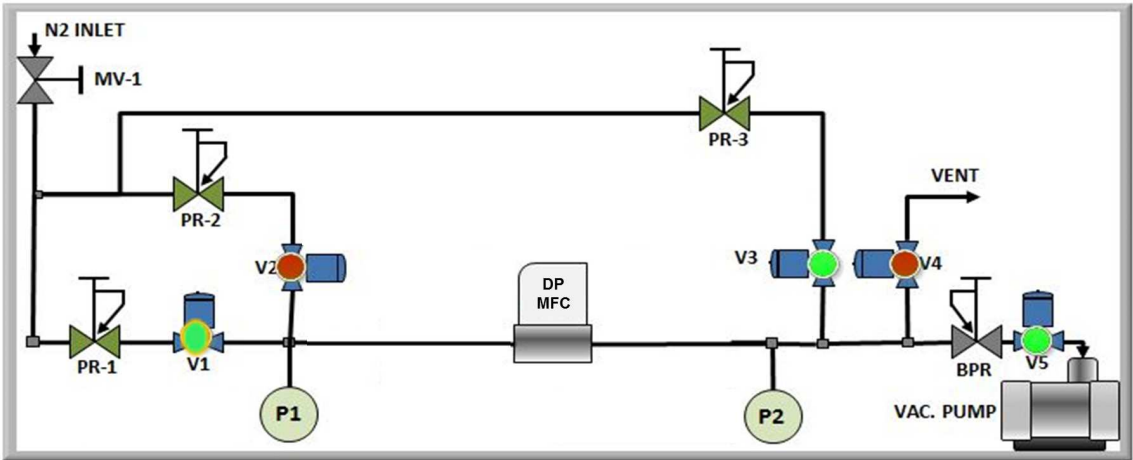


Figure 8: Test setup to evaluate the downstream (outlet) pressure insensitivity of the differential pressure sensor-based MFC.

Figures 9 and 10 show results from this test. For the 500 sccm device, the downstream pressure was changed from ~1 psia (50 Torr) to 20 psia (1100 Torr) in < 2 seconds but the flow remained stable within $\pm 1\%$ of set point. The downstream pressure was changed from 200 Torr to 1100 Torr for the 20,000 sccm device (it was not possible to pump down to a lower starting pressure due to high flow rate of the MFC). As was the case with 500 sccm MFC, the device flow was stable within $\pm 1\%$ of set point. This test showed that the differential pressure based MFC was highly insensitive to downstream pressure fluctuations, making it an excellent candidate for CVD applications.

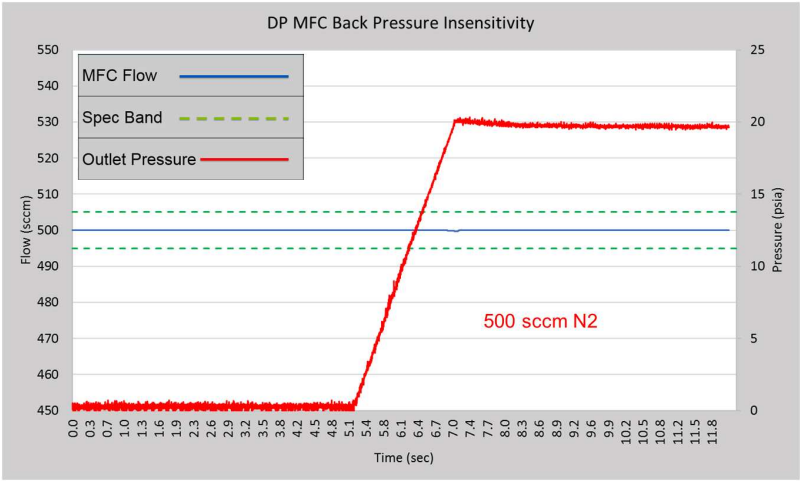


Figure 9: Downstream (outlet) pressure insensitivity data for 500 sccm Nitrogen device.

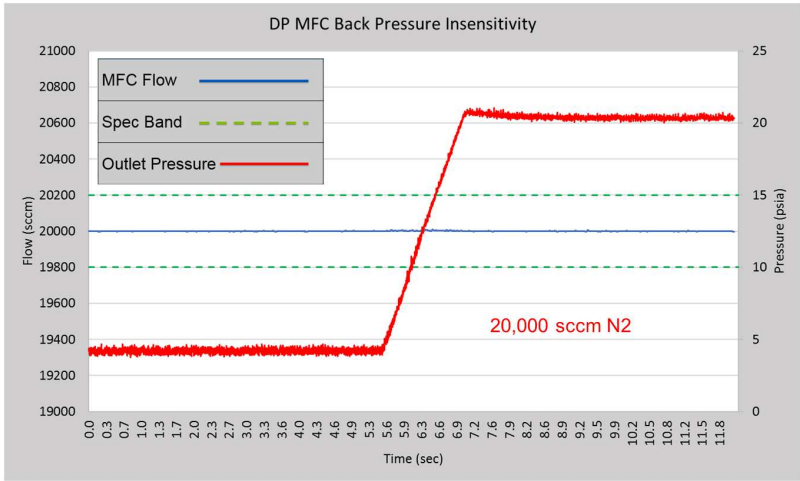


Figure 10: Downstream (outlet) pressure insensitivity data for 20,000 sccm Nitrogen device.

(c) Accuracy Testing

As a part of the performance validation of the differential pressure sensor-based MFC, flow accuracy testing was performed using a Molbloc® placed upstream of the MFC. Molbloc® has a specified accuracy specification of $\pm 0.5\%$ reading. Figure 11 shows the test setup for measuring the flow accuracy of the devices under test.

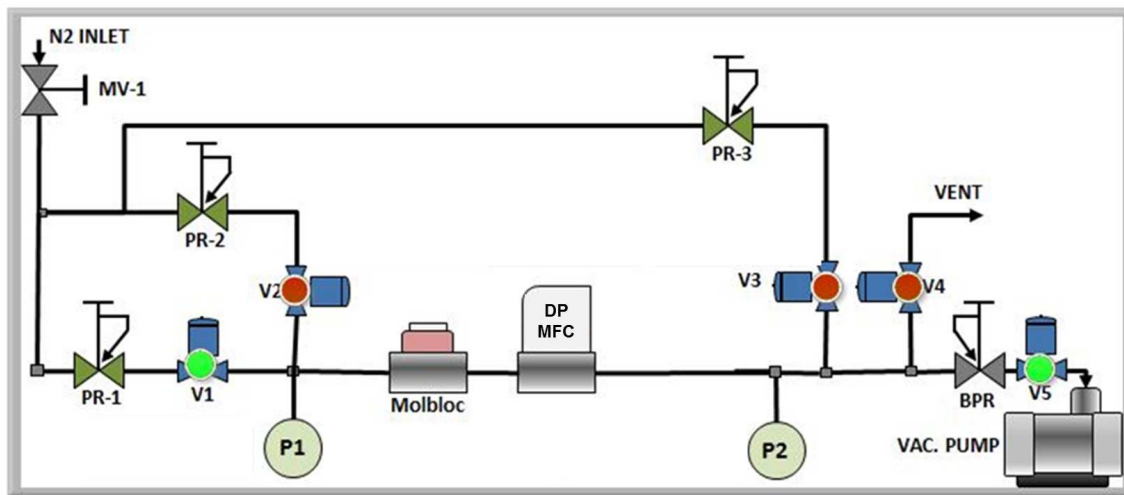


Figure 11: Test setup for flow accuracy testing.

For the purpose of testing, inlet pressure was set at 35 psia and outlet was under vacuum. Since internal gas box temperatures sometimes can reach as high as 60°C (due to many components generating heat inside the gas box), accuracy tests were done both at room temperature (20°C) and 60°C. Finally, tests were also performed on 500 sccm device using Silane (SiH_4) as test gas, since it is a common CVD process gas.

Figures 12 and 13 show the accuracy data for 500 sccm MFC at 20°C and 60°C. The results show that the device holds flow accuracy within $\pm 1\%SP$ from 5 to 100% flow range which is within the stated specification for the differential pressure sensor-based MFC.

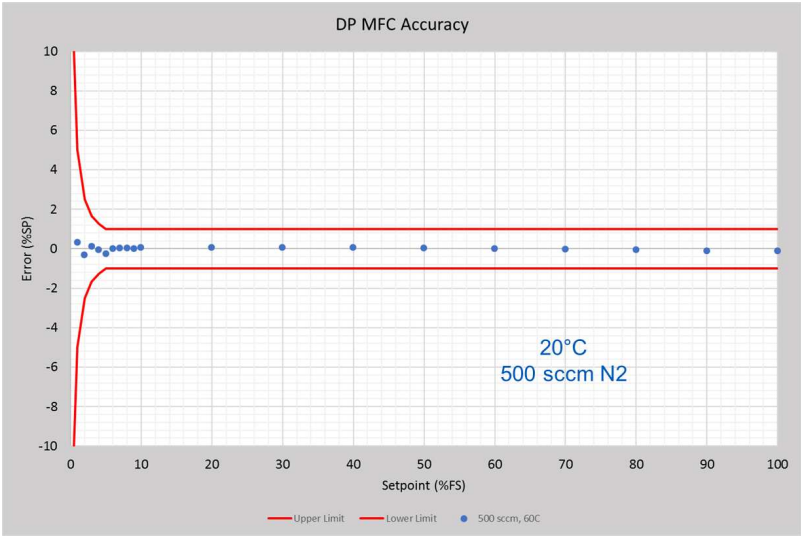


Figure 12. Flow accuracy for a 500 sccm N₂ Differential pressure sensor based MFC at 20°C.

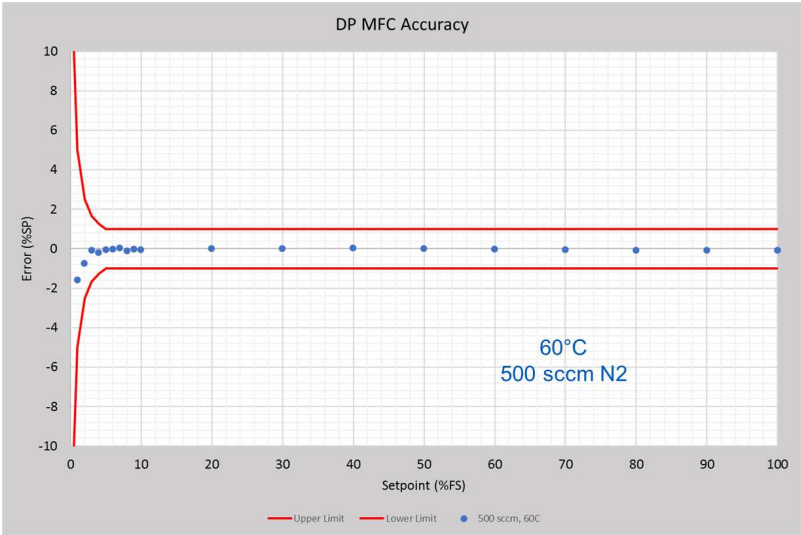


Figure 13. Flow accuracy for 500 sccm N₂ Differential pressure sensor based MFC at 60°C.

The measurement of flow accuracy with Silane was performed in a controlled environment and gas flowing to a rate of rise chamber, which measures flow accurately (has an accuracy specification of $\pm 0.5\%$ reading). Figures 14 and 15 show accuracy data collected using SiH_4 (500 sccm) and 5%B $_2$ H $_6$ in N_2 (500 sccm, 900 sccm and 1300 sccm). With the use of a suitable embedded gas model in the MFC and correct viscosity values, the flow accuracy of the differential pressure sensor based MFC was excellent.

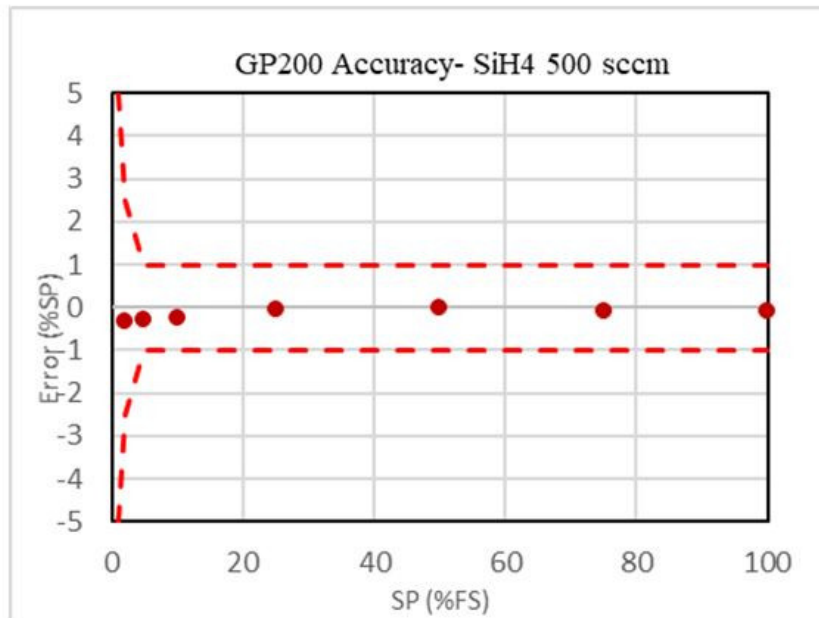


Figure 14. Flow accuracy for 500 sccm SiH $_4$ MFC at 20°C.

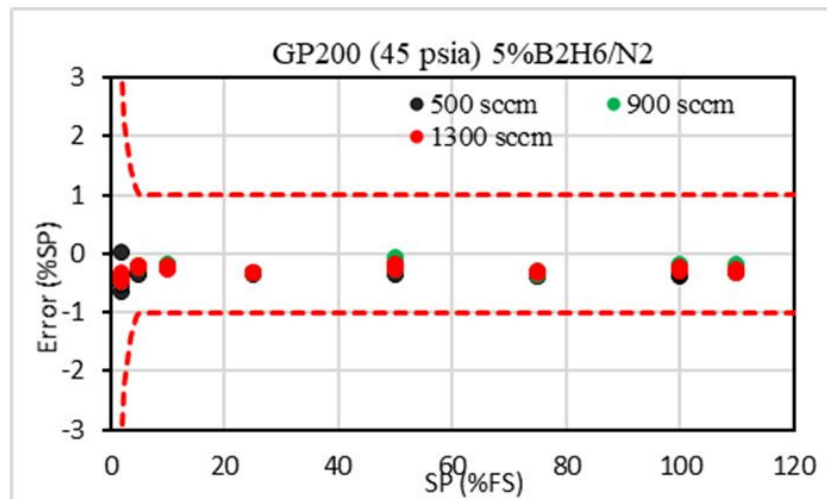


Figure 15. Flow accuracy for 5% B $_2$ H $_6$ in N_2 MFC at 20°C and 45 psia inlet pressure.

Conclusions

A new differential pressure sensor-based Mass Flow Controller is introduced here. Use of a **differential pressure** sensor, as opposed to using discrete pressure sensors for measuring pressure drop and computing flow has an obvious advantage in that it **mitigates the necessity of precisely calibrating and matching individual pressure sensors used in conventional pressure based MFCs**. In addition, **conventional pressure based MFCs** also **suffer from flow inaccuracies** with increasing downstream pressures as well as **tend to be more sensitive to downstream pressure fluctuations**. This will be a limitation when pressure based MFCs are used for CVD processes in semiconductor manufacturing for certain process recipes as the downstream pressure can change from vacuum to more than atmospheric pressures.

The differential pressure sensor used in the new MFC can measure small pressure drops accurately especially at low gas flow rates and is well suited for process recipes involving higher outlet pressures. In addition, since the control valve is positioned downstream of the laminar flow element, they tend to be immune to downstream pressure fluctuations.

REFERENCES

- [1] W. W. White, W. H. White, C. Davis, N. Smith, US Patent 6,539,968 B1, Granted April 2003
- [2] Technical Bulletin, "The Engineer's Guide to DP Based Flow Measurement", Emerson, Inc, #00805-0100-1041, March 2015.
- [3] J. Lull. US Patent 9562796, Granted February 2017.

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