Feature Article

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## Development of a High Accuracy, Fast Response Mass Flow Module Utilizing Pressure Measurement with a Laminar Flow Element (Resistive Element)

### — Criterion D200 Series —

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As semiconductor processes are being scaled to ever smaller sizes, there is a demand for greater accuracy. Wide rangeability is also required for the sake of lower prices. To meet such needs, we have developed a pressure-based mass flow control module utilizing a new technique.

A laminar flow element (resistive element) has a property in which more pressure is lost at a lower pressure and lower flow rate. The Criterion D200 Series utilizes this property to change the error in the flow rate when converting the pressure into the mass flow rate. By doing so, higher pressure sensor output can be maintained when measuring a low flow rate, thereby increasing the flow rate accuracy in the low flow rate region and providing better rangeability. By collecting the data of complex properties of the element and performing numerical calculations, the flow rate can be controlled to a minimum controlled level of 0.3%, achieving six times greater range than with the minimum rate of 2% in the previous MFCs. The new mass flow module is more resistant to variations in supply pressure, because the pressure sensor provides fast response. It meets all the required performance demanded by the next generation processes. The Criterion D200 Series is also equipped with a diagnostic mechanism that utilizes the relationship between pressure and flow rate based on the internal volume of the MFC.

## Introduction

Equipment cost reduction is one of the challenges of semiconductor manufacturing equipment, of which manufacturing of 300-mm wafers is a mainstream today. Moreover, higher integration, increased cost reduction and greater functionality are demanded for the gas panels used to supply process gas. More accurate, highly functional fluid control is necessary with a simple component configuration. This article provides an introduction to the next generation mass flow module, Criterion, which has been developed to meet the needs described above.

## Overview of Criterion D200

Figure 1 shows the external view of the Criterion. This module is designed for semi-standard 1.125-inch applications just like the previous master flow controllers (hereinafter referred to as MFCs) and is compatible with integrated gas panels and connection with the VCR coupling, as previously used, depending on the demand. A display is provided on top of the module to indicate the temperature, pressure, flow rate and other data, and is compatible not only with digital communication protocols such as DeviceNet and RS-485 but also with analog communication protocols as used in the previous MFCs.

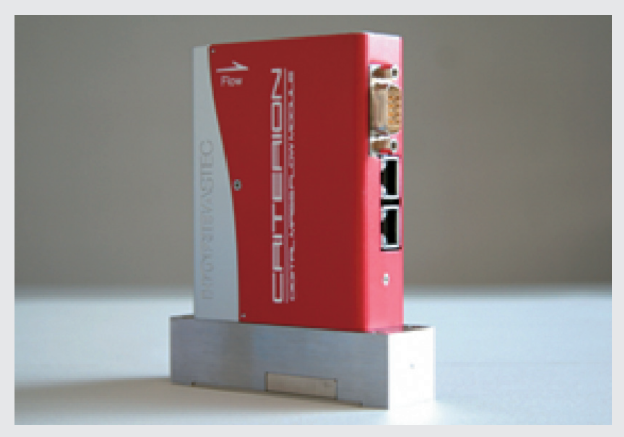


Figure 1 External View

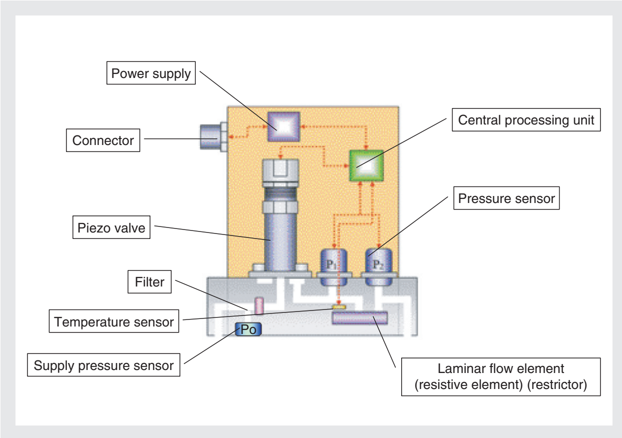


Figure 2 Configuration of the Next Generation Module

## Configuration

Figure 2 illustrates the configuration of the Criterion, which consists of a filter to protect against particles from outside, a line pressure sensor, a control valve, two absolute pressure sensors, a laminar flow element (resistive element) (hereinafter referred to as the restrictor), which is placed in between the two pressure sensors, and an electric circuit, in that order from the gas inlet. The flow rate is sensed by measuring the pressure differential between the pressure sensors placed before and after the restrictor and converting it into the flow rate. A piezo actuator is employed for the control valve, and the areas that come in contact with the gas are all made of stainless steel. The valve's dead volume is minimized. The electric circuit is a digital circuit equipped with a highly precise 32-bit CPU, providing high resolution and various other functions.

## The Previous Method and Its Challenges

The previous MFCs have employed a thermal method in which the mass flow rate is measured from the amount of change in heat distribution inside a capillary tube containing two wound coils. With this method the mass flow rate of the bypassed flow is measured and the flow rate can be calibrated with an alternative gas ($N_2$) by using conversion factors[*1] for different gases. Today this remains one of the most widely used methods.

However, the previous method has the following disadvantages:
- The sensor's response speed is slow (five to 10 seconds); and
- The coils (measuring element) heat up.

To remedy such disadvantages, MFCs have incorporated the following measures and evolved over time:
- PID control for increased speed
- Coil temperature reduction

Nevertheless, the following challenges remain:
- Excessive control is performed when the supply pressure changes; and
- Greater noise is generated when the coil temperature is reduced.

Currently, more stable flow control is achieved by using a pressure sensor to perform the required compensation. While the demand calls for a flow rate sensor with higher speed, the response is delayed because the measurement principle is based on "heat." Therefore, it is necessary to either downsize the coil or come up with another method of measurement.

*1: Conversion factor: A factor of conversion into a gas used. This factor is used when the flow rate is calibrated with an alternative gas.

## Improved Mass Flow Meter Accuracy and Greater Speed of Response

Given the circumstances described above, we have developed a differential pressure-based MFC that calculates the mass flow rate from the pressure. The pressure sensor provides fast response, enabling measurement with a response speed of approximately two milliseconds. It is capable of measuring the pressure with an accuracy that is greater by one digit or more than the ±1% accuracy required for MFCs. Another type of pressure-based MFC is the sonic nozzle type[*2], which utilizes a property whereby the pressure is proportional to the flow rate. Contrastingly, the Criterion has enabled flow control that utilizes the nonlinear properties obtained when a laminar flow element is used in a vacuum. Such flow control has been made possible by completely digitizing the MFC control. A reference flow meter is used to measure and digitize the data regarding the relationship among the pressure upstream of the restrictor (P1), the pressure downstream from the restrictor (P2) and the mass flow rate (Figure 3). The vast pool of such data is used to create the control data, based on which the mass flow rate is calculated from the pressure levels before and after the restrictor in the Criterion in order to control the flow.

*2: Sonic nozzle type: A method by which to measure the flow rate using the critical flow in the nozzle (the condition in which the speed of gas flow inside the nozzle has reached the sound velocity and no longer increases beyond that level). The flow rate is proportional to the pressure upstream of the nozzle.

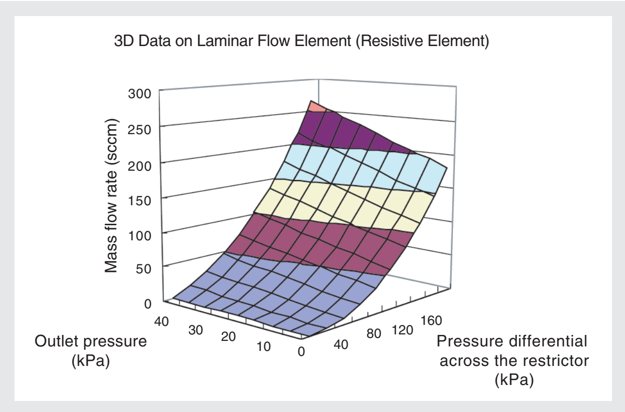


Figure 3 Flow Rate Characteristics with the Laminar Flow Element

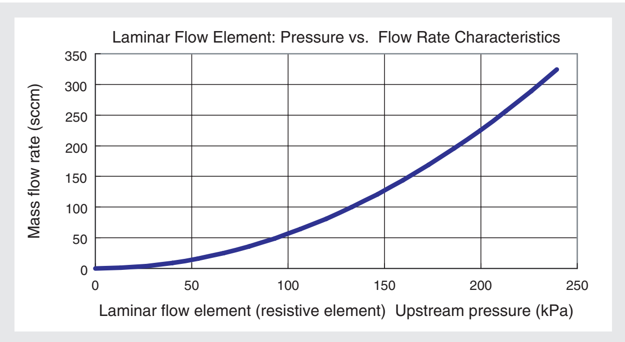


Figure 4 Nonlinear Properties with Laminar Flow Element

In the characteristics of nonlinear pressure vs. flow rate (Figure 4), the pressure differential in the region of low flow is greater than that in the high flow region with a given increase/decrease in flow rate. This enables a higher resolution in the low flow region, thereby allowing for a guarantee of accuracy expressed as a percentage of rate, which ensures even greater accuracy than the accuracy expressed as a percentage of full scale (F.S.). The nonlinear properties enable flow rate measurement over a wider range than can be obtained with the regular linear properties.

While two MFCs were previously used to achieve greater accuracy, a single MFC can now provide the same level of accuracy due to the better rangeability. This helps reduce the numbers of MFCs installed in manufacturing equipment and their related parts that constitute the manufacturing line.

## Approach Toward Guaranteed Accuracy for Actual Gases

The conversion factor used in thermal MFCs is equivalent to the viscosity ratio for the restrictor in the Criterion D200 (Figure 5). Because this ratio changes according to the pressures upstream and downstream of the restrictor as well as the temperature, such gas data must be provided. The viscosity ratio is closer to 1 than the conversion factor and differs less by gas type. While the conversion factor for $SF_6$ is 0.2 to 0.3, the viscosity ratio for this gas is 0.9 to 1.5. Because the conversion value is close to 1, the difference between the flow range obtained during calibration and the flow range obtained by converting the above flow range into that of a gas used can be minimized. We have redesigned the restrictor configuration and made it possible to produce the restrictor in lots in order to manufacture a large volume of laminar flow elements at one time and ensure stable quality. The accuracy of 1% can be guaranteed for actual gases by minimizing the occurrence of variations.

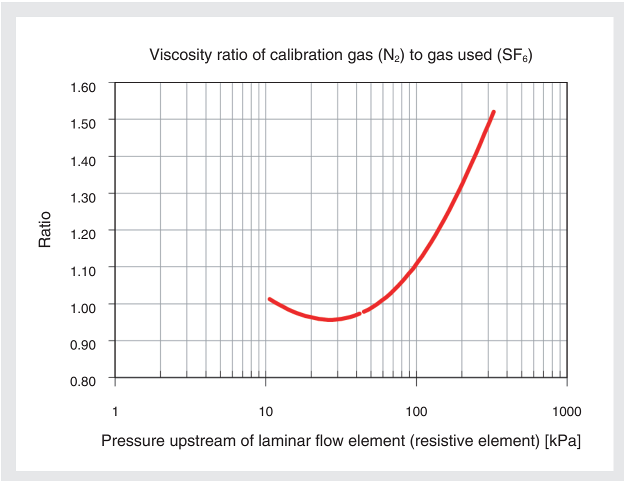


Figure 5 Ratio Data for $SF_6$ ($N_2/SF_6$)

## Pressure Insensitive[*3] (PI) Performance

The flow rate output from the Criterion D200 is a real time indication of the flow rate of the actual gas, because the mass flow rate is calculated from the pressures before and after the restrictor. The Criterion has no time delay, as a thermal flow rate sensor does. While the thermal MFC has a flow rate meter upstream of the control valve, the Criterion has a flow rate meter downstream and thus provides more appropriate PID control for gas control for the chamber. The Criterion functions as a pressure-insensitive MFC (PI-MFC) by performing normal PID control at high speed.

*3: Pressure insensitive: To control so that the flow control will not be affected by the change in supply pressure.

## Additional Self-Diagnostic Function (G-LIFE*4)

Flow testing is performed as part of the self-diagnostic function using the chamber with the following equation:

$$PV = nRT$$

where,

P : Pressure V : Volume n : mol

R : Gas constant T : Temperature

Using the above equation, the internal volume (V) of the MFC is calculated from the amount of change in P1 (after the control valve is closed) and the amount of mass flow released. Based on the assumption that the internal volume does not change for a long time, diagnostic testing is performed by considering the change in volume as the change in flow rate accuracy. Now that the mass flow rate can be measured at a high speed, there is no need to control the mass flow rate to a certain level. Therefore, diagnostic testing can now be performed within a short period of time in which the MFC shifts from the flow control condition to zero flow output. For the commonly used rate of rise (ROR)*5 and rate of fall (ROF)*6, the change in pressure is greater in a given sensor range, so the Criterion is less vulnerable to the effect of sensor noise. High repeatability is achieved, even with the measurement taken within a short time (Figure 6).

While the previous MFCs took a long time to test the flow rate in order to ensure repeatability, the Criterion can take measurements within a shorter period of time and still provide high repeatability. Because the above self-diagnostic testing can be completed within each MFC, it can be conducted even during a process performed with the use of a process gas.

*4: G-LIFE: An abbreviation for Gas Law check of Integrated Flow restrictor Equation.

*5: Rate of Rise (ROR): Flow rate measurement based on pressure buildup. The method of measuring the mass flow rate by measuring the rate of pressure increase within the reference volume.

*6: Rate of Fall (ROF): The method of measuring the mass flow rate based on the amount of decrease in pressure as opposed to the rate of rise method.

## Conclusions

Because MFCs are also used for highly reactive gases, it is important for MFCs to self-diagnose any changes that might occur in themselves over time. Since the flow rate accuracy affects manufacturing processes, it is essential to check the accuracy on a routine basis. However, it remains difficult to prevent the process problems that might be caused by deficiencies in accuracy. G-LIFE diagnoses any change from the initial conditions within seconds. Because diagnostic testing can be done within a short period of time available as spare time, I believe the user of the Criterion can predict maintenance intervals and deal with any unpredicted problems by frequently conducting diagnostic testing.

Pressure and temperature are the most basic data used to understand the conditions within the piping and chamber.

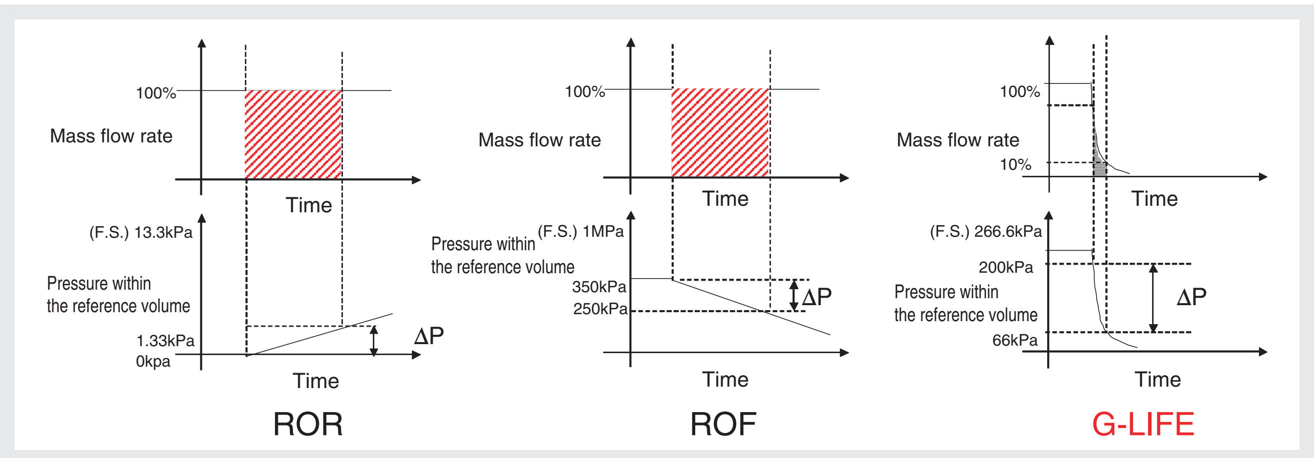


Figure 6 Differences from the Rate of Rise and Rate of Fall Methods Previously Used

The previous MFCs controlled the flow rate without such data, despite the fact that this is an advantage of the thermal flow rate sensor. Meanwhile, in the Criterion the data on restrictor properties has been collected based on the pressure and temperature, thus enabling the following:

- Unheated flow rate measurement without heating the measured media
- Flow rate measurement in a vacuum using highly accurate absolute pressure sensors (this method has no critical point and is ideal for controlling gases with low vapor pressure over a wide range)

We have directed our attention to the above features in addition to the high accuracy and wide rangeability performance achieved with nonlinear properties, in order to release a new MFC model that is compatible with the unheated, low pressure, high temperature conditions. The new model is intended for use with materials for the transparent electrode (TCO) in solar cells that have been in use during recent years. The lack of any heated element will be a great advantage for TCO materials, which easily decompose due to heat, and highly corrosive materials.

I believe that pressure-based MFCs or MFCs that utilize pressure sensors will be in mainstream use in the years to come. Particularly, I think pressure-based MFCs will be able to contribute to cutting-edge technology. While previously the user needed to have certain levels of knowledge and experience in order to use an MFC, there is no such requirement with the Criterion. The flow rate accuracy is neither dependent on the supply pressure nor the direction in which the Criterion is oriented upon installation. All that is needed is to check whether the flow rate set in the Criterion matches the output. The data obtained to calculate the flow rate is used to allow the Criterion to function as a mass flow module. I believe we will be able to provide ever greater value by offering new applications with the use of the Criterion.

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