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Eliminating the effects of
gas-system pressure transients

OVERVIEW Every time a mass flow controller in a multichamber installation shuts off or reopens, it can affect system pressure and flows. The combined effects of components reacting to pressure changes disseminates "crosstalk" through the system, disrupting low-flow MFCs in other chambers and tools. It is common to add pressure regulators immediately upstream of MFCs, which are highly sensitive to pressure transients, but this can also interfere with normal MFC flow stability. From an analysis of such problems, we developed a mass flow control concept that combines proven thermal and pressure-based techniques in a new hybrid flow controller. The controller effectively isolates itself from both upstream and downstream pressure changes, thus eliminating the need for local pressure regulators and associated hardware from the space-constrained gas box.

Rapid pressure transients are common in complex gas distribution systems used in semiconductor manufacturing. Flow dynamics in a gas control system and the operation of control components such as pressure regulators, valves and mass flow controllers (MFCs) generate pressure transients. These transient changes in gas pressure upset normally steady outputs of MFCs. Process problems frequently result and can be difficult to diagnose, contributing to tool downtime.

Opening a valve can take a gas line from vacuum to well above atmospheric pressure in a fraction of a second. Changes in flow due to resistance in a gas line can modify outlet pressure. Higher flow and more restriction generate a larger pressure drop. This is the fluid equivalent of Ohm's Law. At sufficiently high flows, the resistance becomes nonlinear, increasing sharply as flow increases. Examples of flow restrictions include long runs of small-diameter tubing, sharp bends, valves, filters, purifiers, pressure regulators, and flow limiters. When flow changes in any part of a system, the resulting pressure alteration appears at every point that shares the same supply resistance.

Pressure regulators are an integral part of a distribution system for compressed gases. They establish a relatively stable, known upstream gas pressure that feeds many process chambers. Demand on a shared distribution regulator is highly variable as multiple process tools cycle gas on and off. These regulators produce short-term pressure transients as they strive to maintain constant pressure with a constantly changing load. Transients often disrupt MFCs flowing at the time, causing seemingly random process anomalies.

The conventional solution to tool interactions coupled through a gas supply has been to add more levels of pressure regulation. Many installations now contain a dedicated pressure regulator for each MFC. An alternative solution, presented here, eliminates MFC sensitivity to pressure transients.

MFCs and pressure transients

Insensitivity to gas pressure is a rule inherent in the concept of mass flow. Although the volume occupied by gas molecules is a direct function of pressure and temperature, today's MFCs are virtually insensitive to those variables. An MFC meters out whatever volume of gas is required to deliver the desired molecular flow rate. This rule is common knowledge in the industry; however, many do not realize that there is a significant exception. The rule is true only if gas pressure at the MFC is stable over time.

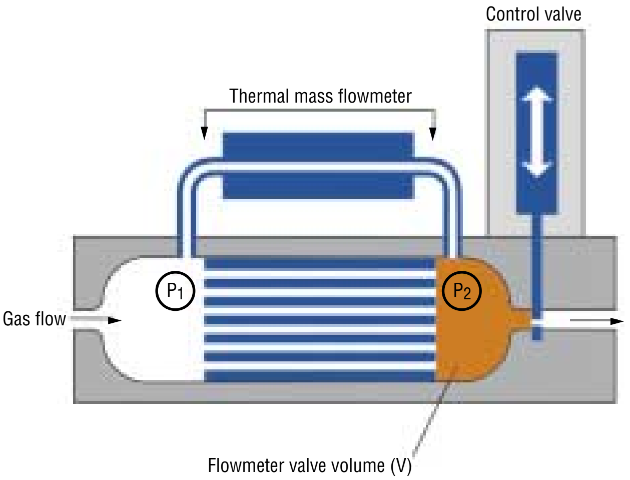

Figure 1. The volume between the flowmeter and control valve in a conventional MFC.

Conventional MFCs are sensitive to pressure transients due to their physical architecture and the nature of their control systems. Most MFCs contain a flow meter followed by a proportioning control valve. The flow through the meter exactly equals the flow through the valve under most conditions. This permits very tight, closed-loop control of flow. As shown in Fig. 1, there is a small internal volume (V) between the flowmeter and the valve. There is virtually no flow resistance in the flowmeter. Consequently, the pressure (P_2) in V must equal the

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inlet pressure (P_1). If P_1 rises, slightly more gas flows through the meter than flows through the valve to raise P_2 to P_1. If P_1 falls, slightly less gas flows through the meter than through the valve so that P_2 again becomes equal to P_1.

In this way, pressure changes appear as small flow errors proportional to the size of V. MFC designers locate the valve as close as possible to the flowmeter in order to minimize V, which is nearly impossible to eliminate.

A rapid change in inlet pressure creates a relatively large flow error for a short time. An MFC control system responds very quickly to this flow error. Because the error lasts for such a short time, a control system tends to overreact. Momentary instability results. This often causes a flow disruption of much greater relative magnitude than the original transient.

The hallmark of a pressure-transient flow disruption is the inverse relationship between an MFC's indicated flow reading and the actual flow. A very fast-responding flow sensor connected to an MFC can measure actual flow. Figure 2 shows three parameters from a 20sccm MFC transient event: change in inlet pressure caused when a 2slm MFC on the same supply turns on; flow disruption reported by the MFC; and actual flow.

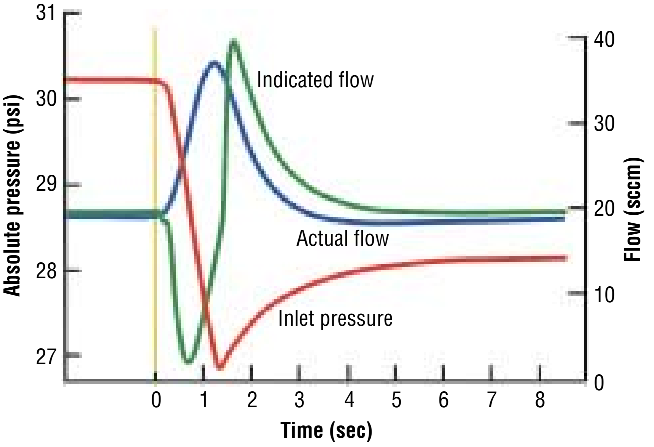

Figure 2. The effect of an inlet pressure transient on a conventional MFC.

The MFC indicates a flow spike of the same polarity as the pressure transient. The actual flow spike moves opposite in polarity. This relationship exists due to the manner in which the MFC drives its control valve to correct for perceived error. If the flow error is positive, a control valve will move to reduce flow. After the transient passes, an MFC will open the valve again. A dampened oscillation may continue in the gas flow for a few cycles until the system recovers equilibrium.

Figure 2 shows one full cycle. The magnitude and shape of these curves vary with MFC and system design, but the relationship holds for all conventional thermal MFCs.

Pressure-transient sensitivity is directly proportional to V. The error magnitude is independent of flow. The effect is most disruptive at very low flows, where V is a larger fraction of gas flow during the pressure transient. Because the effect is proportional to volume, mass flow error increases with gas density. High-molecular weight and high-pressure gases are most strongly affected. Unless the pressure transient is significant, it is usually unnoticeable above a few hundred sccm.

The classic problem manifests in multichamber tools where multiple MFCs connect to the same gas supply. When a flow of several liters cycles on and off, it affects supply line pressure. Low-flow MFCs, especially those below 100sccm, may react strongly to these pressure changes. If the process is sensitive to flow upset, the effect may be noticeable on wafers.

Sometimes, the transient spike in MFC flow output may be significant enough to exceed tool alarm limits, shutting down a process. This "crosstalk" effect between processes may appear to be random because processes are not synchronized. The conventional solution to this problem is to install a separate pressure regulator for each MFC. This approach helps in many cases. It can also cause problems of its own, as discussed below.

Pressure regulators

Mechanical line pressure regulators reduce distribution gas pressure to the appropriate value for an MFC. A regulator throttles its internal valve to maintain a set outlet pressure over a wide flow range. Outlet pressure can vary significantly, however, from its nominal setting as flow changes.

As flow through the regulator increases, outlet pressure falls. This "droop" varies with regulator design, but tends to be more pronounced at the lower end of a regulator's operating range. If flow changes abruptly, a regulator may not respond instantaneously. This can extend the effect. In the case shown in Fig. 2, the regulator takes more than 5 sec to stabilize pressure. As long as pressure is changing, the 20sccm MFC does not recover its setpoint flow.

At very low flows, where MFCs are most sensitive, regulators can generate periodic pressure transients. When flow is shut off downstream, a regulator's outlet pressure will rise until the internal force closes its valve, so-called lockup pressure increase. If flow remains shut off for a time and the valve does not seal completely at lockup, outlet pressure will gradually creep higher until the regulator seals. When flow resumes, the pressure will fall until the regulator opens. A trickle flow is required to keep the regulator constantly flowing at the pressure where its valve first opens. Lockup is typically 2–10psi higher than pressure at trickle flow. Trickle flow may be 200sccm. All of these parameters are dependent on regulator design.

At some level below the trickle flow rate, a regulator may cycle between a flowing and shut-off condition. The cycle time depends on downstream plumbing volume and lockup pressure. With the regulator shut off, pressure in the outlet volume decays until the regulator opens. Outlet pressure then increases rapidly to lockup and the cycle repeats with a sawtooth waveform.

Figure 3 shows closely coupled regulator-MFC interactions from field data. Pressure starts relatively high due to creep. The MFC begins its initial response very quickly. Pressure drops almost instantaneously because the regulator is closed and the gas inventory between the regulator and MFC is small. This fast pressure drop causes the MFC to execute a deep reversal in its response curve. As the MFC resumes its climb to setpoint, inlet pressure continues to drop. The falling pressure affects the MFC, so the second rise to setpoint is considerably slower. As the MFC nears setpoint, the regulator opens for the first time and pressure increases until the regulator reaches lockup.

The cycle of inventory depletion, regulator opening and lockup repeats two more times. On the last cycle, the regulator does not completely close and pressure stabilizes. The tail of the pressure waveform becomes thick because the regulator is actually oscillating at ~120Hz. MFC flow responds to each pressure change except in the final oscillation, which is too fast for the MFC to follow.

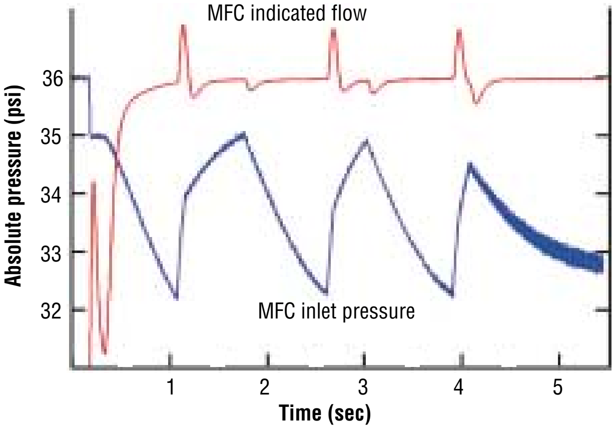

Figure 3. Interactions between a closely coupled pressure regulator and a conventional MFC.

Gas systems built to today's standards are essentially particle-free. The regulator is, however, one of the few components that actually generates particles in normal operation. Because this characteristic is very difficult to avoid, filters are included in most tool gas sticks to trap these particles.

Regulators must shut off without leaking. Otherwise, outlet pressure would creep until it equaled inlet pressure. The regulator valve must be very efficient mechanically because the closing force provided by the pressure-sensing diaphragm is limited. If the valve is not efficient, lockup and creep pressures will be excessively high. Tapered conical poppets typically wedge tightly into circular seats to achieve a good seal with minimal force. The sliding friction of the poppet and seat, however, can create particles. Because a gas stick regulator must seal and reopen during every process cycle, this friction is unavoidable.

Pressure compensation

New pressure transient-immune thermal MFC technology is immune to upstream and downstream pressure changes. This can eliminate the need for local pressure regulation and other associated components in tool gas boxes. It can result smaller, less-expensive, better performing and more reliable systems.

A pressure transient-immune thermal MFC is built around a proven thermal mass flowmeter. It uses a fast electromagnetic proportioning valve and a nozzle plate to control flow and to shield the mass flowmeter from external conditions. The proportioning control valve located in front of the flowmeter functions as part of an upstream isolation system. Adding a fixed nozzle behind the flowmeter provides a pressure drop that isolates the flowmeter from the downstream environment.

Regulating flow is a two-step process. The proportioning valve maintains an intermediate internal pressure at the level that will deliver the desired flow through the outlet nozzle. Pressure transient-immune thermal MFCs combine aspects of both thermal and pressure-based flow control. To prevent confusion of similar features in pressure transient-immune thermal MFCs and pressure-based MFCs, a discussion of both follows.

Like pressure-based MFCs, pressure transient-immune thermal MFCs rely on a flow restriction to isolate the MFC from downstream effects and use an upstream valve to regulate internal pressure. In contrast to pressure-based designs, they use a well-characterized thermal flow sensor to predict flow rate rather than relying on modeling the behavior of process gas flowing through a critical nozzle. Like pressure-based MFCs, they are immune from upstream pressure variations, thus dramatically simplifying a gas delivery system by eliminating pressure regulators dedicated to MFCs and their auxiliary components.

Critical flow

A flow nozzle is a small, relatively short restriction in a gas pipe. Because it is a restriction, the gas loses pressure as it forces its way through the nozzle. Being the smallest part of the pipe, the nozzle limits the rate at which gas flows. As gas flows through the pipe, it speeds up as it passes through the nozzle. At relatively low velocities within the nozzle, the flow in the pipe is proportional to the square root of pressure drop across the nozzle — the difference between upstream and downstream pressures.

As upstream pressure increases, prompting flow through the nozzle to reach the speed of sound in the gas, this relationship changes. At that point, downstream pressure no longer matters. The speed of sound is as fast as gas will flow through the restriction — a condition described as sonic flow or critical flow. A typical rule of thumb is that critical flow occurs when upstream pressure is more than twice downstream pressure. At critical flow, downstream pressure can range from vacuum to almost half of upstream pressure without affecting flow rate. A nozzle under critical conditions will not pass pressure transients upstream.

If upstream pressure continues to increase beyond where nozzle flow becomes critical, the mass of gas passing through the nozzle increases, although its velocity remains constant. The density of the gas within the nozzle simply increases, moving more mass at the same velocity. Under critical conditions, the mass flow rate of ideal gases through either is directly proportional to the upstream pressure.

It is possible to use this property of critical nozzles to create MFCs that do not work on conventional thermal principles. Pressure-based MFCs use a pressure transducer and a fixed critical nozzle behind a proportioning valve. The valve and pressure transducer set the pressure upstream of the critical nozzle, thereby controlling the flow.

Upstream transients

Conventional thermal MFCs are sensitive to pressure transients because their flowmeters are not isolated from the upstream environment. Shifting a control valve to the upstream side of an MFC and using it to control internal pressure largely suppresses inlet pressure transients. The difference between inlet and outlet pressures of an MFC usually exceeds 2:1.

In a pressure transient-immune thermal MFC, the control valve and a nozzle on the downstream side of the flowmeter divides this differential pressure. The flowmeter contributes <5% of the device pressure drop at full scale. Both inlet and outlet restrictions reach critical flow operating into vacuum. The control valve behaves as a variable critical flow nozzle. The MFC electronics constantly adjust the valve drive and the resulting nozzle size in response to any detected flow error.

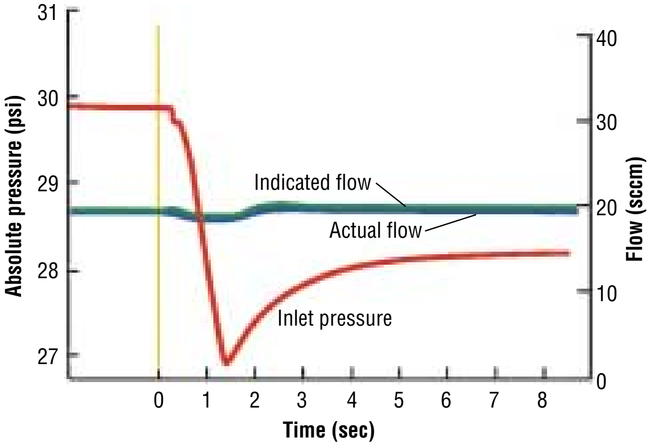

Figure 4. The effect of an inlet pressure transient on a pressure transient-immune thermal MFC.

An inlet pressure transient will produce a change in flow through the control valve as it would with any critical flow nozzle. A fast 10% absolute pressure spike would produce a flow spike of similar polarity and magnitude through the control valve. This assumes the valve does not change position throughout the event.

In the pressure transient-immune thermal MFC, however, the control valve does not establish gas flow independently. The control valve establishes upstream pressure for a nozzle on the downstream side of the flowmeter. The pneumatic time constant provided by the resistances of the control valve and the downstream nozzle, together with the internal volume of the flowmeter, form a low-pass filter that attenuates the fastest portions of the transient. Simultaneously, the mass flowmeter senses the more gradual flow error and appropriately adjusts the control valve to mitigate the effects of the transient. The resulting flow error at the MFC outlet is <1% (Fig. 4). An identically sized conventional MFC produces an outlet flow error of >75% with the same stimulus (see Fig. 2).

Critical nozzle MFCs (pressure-based) also employ an upstream control valve followed by a nozzle. Unlike the pressure transient-immune thermal MFC, their principle of operation requires the downstream nozzle to maintain critical flow under all conditions. Therefore, they require more than a 2:1 pressure differential to operate both restrictions in series. This typically requires higher supply pressure when feeding atmospheric pressure processes. The pressure transient-immune thermal MFC does not require either restriction to operate in critical flow because a fast thermal sensor still measures the flow.

Based on established thermal measurement techniques, pressure transient-immune thermal MFCs rest on a large body of experience using MFCs with exotic process gases. This permits the use of pressure transient-immune thermal MFCs without concern that process parameters may shift, requiring recipe changes and revalidation of process.

Because critical nozzle MFCs employ a different measurement principle than thermal MFCs, they must compensate for different variables in gas properties and environmental conditions. These properties may not be well known for some process gases. Gases supplied not very far above their dew point behave differently in critical nozzles compared to commonly available calibration gases.

Downstream effects

The critical pressure drop across a control valve in a conventional MFC effectively isolates it from the downstream environment. Accordingly, the industry has generally ignored the downstream pressure environment. Chamber vacuum reaches back to every operating MFC, although the conductance of typical gas supply lines is low. Pressure transients do occur in outlet-mixing manifolds and similar structures. The poor conductance of the chamber supply lines exacerbates pressure transients as additional gases are switched in and out. Particularly in vacuum systems, isolating the flowmeter from the downstream environment is prudent.

In the pressure transient-immune thermal MFC under vacuum process conditions, the downstream nozzle operates in critical flow. Under critical conditions, as previously discussed, downstream pressure variations are isolated from the flowmeter.

At higher process pressures where the downstream nozzle may not operate in critical flow, the resistance it supplies, together with the volume of the outlet piping, constitutes an external pneumatic filter that mitigates the effect of fast pressure transients. Above vacuum conditions, however, there are few mechanisms to create outlet side pressure disturbances that are a significant fraction of the absolute pressure. The isolation provided by the downstream nozzle is generally effective under any practical conditions.

Conclusion

Sensitivity to pressure transients remains a chronic problem with semiconductor gas delivery systems. Because transient effects are elusive by nature, they are difficult to predict or diagnose. The industry has responded by adding pressure regulators and associated hardware to every tool gas line as precautionary measures. New problems created by this approach are not widely understood. The most sensible solution to problematic pressure transients is to eliminate their root effect in MFCs. Using well-characterized calibration factors of thermal mass flow sensors, new pressure transient-immune thermal MFCs combine features of both thermal and pressure-based MFC designs and eliminate the need for pressure regulators and associated components. ■

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