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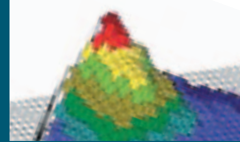
SEMICONDUCTOR® Manufacturing



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MATERIALS: PROCESS CONTROL

Beyond Pressure Transients: Using Pressure-Insensitive Mass Flow Controllers to Control Gases In Semiconductor Manufacturing

By R. Mike McDonald, Advanced Energy

MASS FLOW CONTROLLERS WERE INVENTED IN the 1960s in conjunction with NASA's Apollo program and quickly found use in the then-embryonic semiconductor manufacturing industry. The technology has undergone a variety of changes in both embodiment and performance. From the days of manually-operated devices which often required more than 30 seconds to achieve set-point and suffered from +/- 30 percent errors [1] to today's high-speed, high-accuracy, high-reliability, automated multi-function devices, the MFC has seen a great deal of evolution.

The most recent major step forward in MFC technologies used in the semiconductor industry is the birth of a generation of devices known as pressure-insensitive MFCs, or PIMFCs. As the moniker implies, one of the primary benefits of this type of device is its ability to withstand pressure changes in the gas supply line. The inclusion of both pressure and temperature sensors allows the PIMFC to provide visibility of operating conditions that have a profound impact on mass flow control. While the concept of an integrated mass flow controller, pressure transducer and temperature sensors have been studied for a number of years [2], market demands have only recently provided the impetus for commercialized devices.

Real-time monitoring of the pressure in conjunction with active control of the valve allows the PIMFC to withstand sudden pressure perturbations in the gas line stemming from cross-talk (adjacent MFCs opening and closing), upstream regulators drooping or popping, downstream events occurring in the chamber, and so on. This level of pressure insensitivity alone offers a tremendous amount of overall cost reduction in the gas stick as the PIMFC consolidates the functionality of what has been four independent devices (regulator, pressure transducer, temperature sensor and MFC) into the footprint of a single traditional MFC as shown in Figure 1.

Rightfully so, there has been a great deal of focus on the economic motivations [3] of the PIMFC. Obviously, removing a pressure regulator, pressure transducer and all associated substrates and seals equates to a significant cost savings and reliability improvement. Something not as immediately apparent is that the addition of the integrated pressure transducer and temperature sensor offer performance improvements that are extremely compelling. This paper will explore some of these extended benefits of the PIMFC.

RECENT TRENDS IN MFCS

MFC vendors have been actively developing several technologies focused on reducing cost and improving performance. Three key advances that build upon one another are referred to as multi-gas/multi-range (MGMR), nitrogen (N_2) cal-only and pressure insensitive mass flow controllers (PIMFC).

MGMR is a drive to reduce the number of MFC "sizes" needed to cover the full range of flow. It is an approach that allows the user to configure a device to operate within a range of full scales and across an array of gasses. In semiconductor applications, the bulk of MFCs operate over a range of 10 sccms (standard cubic centimeters per minute) to 30 slms (standard liters per minute). If a given MFC "size" can be manufactured such that it can be easily configured by the user to operate over a wide range of flows, only a few "sizes" are needed to serve all applications in this flow spectrum. MGMR MFC manufacturers are able to address the aforementioned range of 10 sccms to 30 slms with anywhere from seven to 12 different sizes (depending on the manufacturer's design). Using single gas MFCs to cover the same flow range across the variety of gasses and numerous processes at a typical manufacturing site can require hundreds of different MFC models. This

multi-range capability greatly reduces the number of devices which need to be maintained as part of a fab's spares pool.

Further simplifying the use of MFCs has been the advent of the multi-gas technology. MFC vendors have focused a great deal of R and D effort to better understand how different species of gasses behave under a variety of conditions and on embedding this information inside the control logic of the MFCs. Today's MFCs can be reconfigured easily by the end-user via simple software. This configurability allows the PIMFC to be put into service measuring and controlling any of a variety of actual gasses without any costly and time consuming recalibration/retuning. Together, multi-gas and multi-range technologies are aggressively driving down the size of the spares inventory required to support end users.

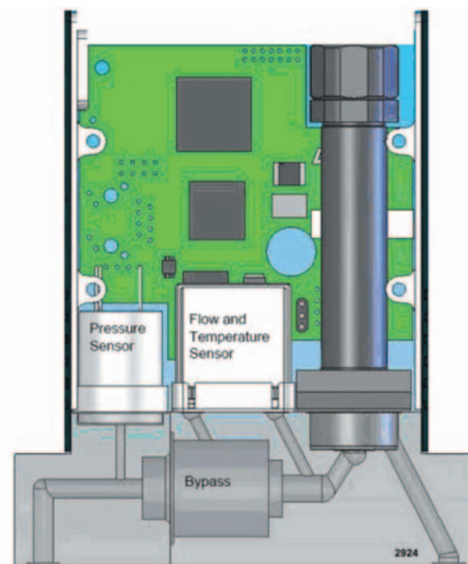
Practical limitations have required that MFCs be calibrated using safe and relatively inexpensive surrogate gasses. Most multi-gas MFCs are calibrated using a number of different surrogate gasses each representing a "family" of gasses which possess similar flow characteristics. A first approximation of actual gas flow through a device calibrated with a surrogate gas can be had by a simple ratio of specific heats (Cp) between the calibration gas and actual gas. Many multi-gas MFCs still use this simple scalar approach to calculate the conversion factor (CF); however, with ever-increasing requirements for tighter process controls, this method has been found to be an inadequate oversimplification. Cp is well known to be a strong and non-linear function of both pressure and temperature. Moreover, the nature of the inter-dependencies is very different among different process gasses and mixtures. Sophisticated models have been developed to account for many of these pressure and temperature inter-dependencies.

An emerging trend is the development of correlations necessary to calibrate and tune MFCs using nitrogen only. This approach reduces manufacturing and service costs as well as improving consistency, since only one set of calibration and tuning data is referenced for operation for all actual process gasses. While a seemingly obvious and simple step from MGMR technology, the models correlating the full field of process gasses to a single gas used for both calibration (measurement) and tuning (response to a set-point change) are very involved.

FIGURE 1

PIMFC simplification of the gas stick.

FIGURE 2



PIMFC architecture.

PIMFC PERFORMANCE ADVANTAGES

With the addition of pressure and temperature measurement capabilities (see Figure 2), the PIMFC now has full visibility of all terms in the ideal gas law PV=nRT. This new information allows for the compensation of known pressure and temperature dependencies in such key gas properties as density, compressibility factor (Z), specific heat, viscosity, thermal conductivity and vapor curves. Models accounting for higher-order effects due to, among others things, the realities of caloric and thermal imperfection in many gasses, greatly improve three important areas: accuracy, speed of response and self-diagnostics.

Accuracy of the PIMFC is improved with the inclusion of gas models that compensate for readings that are otherwise affected by pressure and temperature. Owing to the need to understand precise flows, MFC manufacturers have a great deal of proprietary information that has been collected through years of testing and calibration using equipment that measures temperature and pressure for specific process gasses. The advent of the PIMFC allows this information to be used in the mass flow models to compensate for pressure and temperature effects.

To quantify this accuracy improvement, a group of traditional MGMR MFCs from various vendors were subjected to accuracy tests under a profile of changing pressures, temperatures, user full scales and gas types (N_2, Ar, He and SF_6). An identical population of PIMFC units was submitted to the same battery of tests. The results are shown in Figures 3 and 4.

As demonstrated by the data, the 3σ error for the standard MFC is greater than 1.5 percent while the 3σ error for the PIMFC is much tighter at less than 0.5 percent. The additional process visibility afforded to the PIMFC gives it much better accuracy and repeatability.

Speed of response is likewise improved as pressure and temperature effects on viscosity and density can be used to adjust control tuning parameters. With the new information, tuning parameters can be adaptively and optimally set for the specific process gas and operating conditions.

Settling times are becoming increasingly important in mass flow controllers as new process technologies [4] are demanding both fast dosage rates as well as consistent, measurable molar amounts. State-of-the-art PIMFCs are offering viable options to simple binary valve technologies when addressing speed objectives such as those presented by atomic layer deposition (ALD) processing.

To obtain a measure of the improved speed performance of PIMFC technology, the same devices used to determine the accuracy metrics above were subjected to series of response-time tests. The results are highlighted in Figure 5.

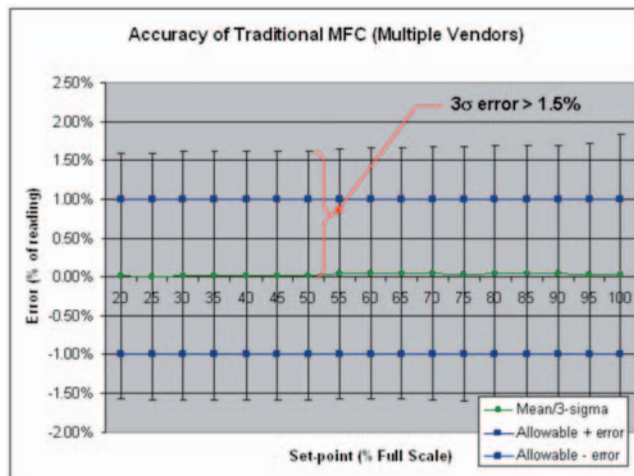
Some of the traditional MFCs had trouble meeting their own specifications of a 1.0-second settling time. PIMFC devices are achieving less than 500 msec consistently with typical value around 350 msec. The need for speed will continue to drive these settling times lower and lower. Sub-100 msec settling times are currently under development.

Self-diagnostic capabilities are enhanced with the additional process information afforded to the PIMFC. An International SEMATECH study found that 70 percent of the time there is “no MFC trouble found [5].” Removing and replacing an MFC can be very costly, time-consuming and, in some cases, dangerous. Replacing an MFC results in about two hours of downtime and tens of thousands of dollars in lost production costs [6]. The added process monitoring capabilities of the PIMFC enable it to conduct self-diagnostics assessments previously unheard of and enable MFC manufacturers and process engineers alike to more quickly drive to root cause.

As an example, the new pressure and temperature sensors allow the PIMFC to make a constant assessment of the thermal flow sensor’s accuracy. Pressure drop, dP_2, across the controlling valve of an MFC is a model that is approximated by an equation which can be empirically determined and is dependant on the following variables:

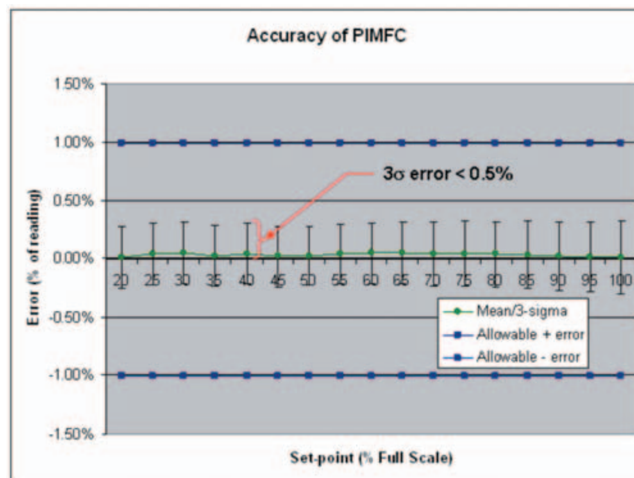
$$dP_2 \sim f(VVH, P, T, \dot{m}, gas_type)$$

FIGURE 3



Characteristic MFC accuracy under changing pressure, temperature, user full scales and gas types.

FIGURE 4



PIMFC accuracy under changing pressure, temperature, user full scales and gas types.

Where VVH is valve voltage history that accounts for the known hysterisis in the valve. Once dP_2 is approximated, the known process, or downstream, pressure (supplied to the PIMFC through software configuration) can be used to derive an approximation of mass flow for a given gas according to the following calculation:

$$\dot{m} = C(\mathrm{Re}) * dP_1 * \rho(T,P) \Big/ \eta(T,P)$$

where dP_1 is the pressure drop across the flow sensor and bypass assembly. The calculation assumes laminar flow

and is a function of the Reynolds number, Re, which is a unique property of the valve inlet, bypass assembly and flow sensor specific to each MFC manufacturer's design. The correction function C (Re) is determined empirically as specific for size, make and model of the valve.

The approximated mass flow can then be compared to the more precise flow as measured by the flow sensor shown in Figure 6.

Where for a given gas or mixture $\dot{m} = Voltage * CF(P, T, Voltage, gas_type)$. CF in this equation is the same CF discussed previously and is a function that includes gas type, measured voltage, pressure, temperature and other parameters associated with the sensor and bypass design. Again, these complex models are unique to each style and manufacture of MFCs.

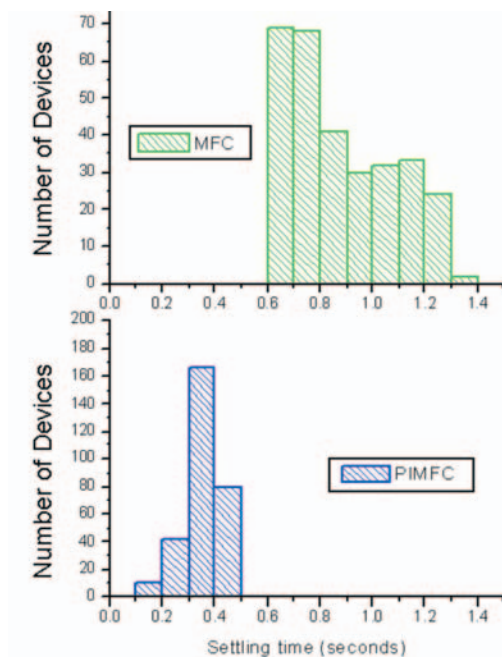
The $\dot{m}$ detected from the temperature sensor, pressure transducer and valve voltage can be continuously monitored and compared to the mass flow measured by the thermal mass flow sensor. Errors originating from sensor drift can be detected by this comparison and sent to the tool controller for early notification. Additionally, if a PIMFC is suspected to be problematic, specific self-diagnostics can now use pressure and temperature to assess equipment health and avoid the replacement of a properly-functioning MFC that are costly for both the equipment manufacturer and the end user.

CONCLUSION

The research efforts which drove the development of PIMFC technology were energized by cost reductions which are easily realized on systems requiring pressure regulation at the gas stick. Additional benefits including improved accuracy, reduced settling time and enhanced self-diagnostics have been identified as derivative benefits of this technology. PIMFC technology delivers increased process control capability and enables advanced process development, driving ever-decreasing node sizes in semiconductor manufacturing.

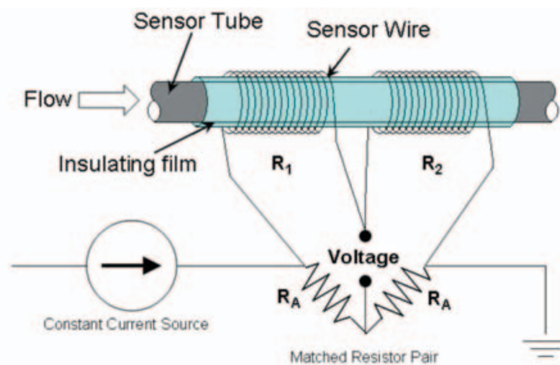
R. Mike McDonald is the director of flow engineering at Advanced Energy, where he has been employed since 2001. His work is focused on the development of flow delivery technologies for semiconductor and industrial processes. His responsibilities include the development of AE's new pressure-insensitive mass flow controllers, high-fidelity gas dynamics models and next-generation vapor delivery systems. Prior to joining AE, he founded and managed Mavin Technologies Inc., a company providing advanced process control solutions and technologies. Mr. McDonald is a graduate of the University of Utah, where he earned his degree in electrical engineering.

FIGURE 5



Comparison of settling times for traditional MFC vs. PIMFC.

FIGURE 6



Flow sensor model.

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