Microfluidic MEMS for Semiconductor Processing

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Abstract

The advent of MEMS (microelectromechanical systems) will enable dramatic changes in semiconductor processing. MEMS-based devices offer opportunities to achieve higher functionality, at lower cost, with decreased size and increased reliability.

In this work, we describe the achievement of several important devices for use in the semiconductor equipment industry. They include a low-flow mass flow controller, a high-precision pressure regulator, and an integrated gas panel. Compared to current technology, the devices are ultra-small in size, thus minimizing dead volumes and gas contact surface areas. With wettable surfaces comprised of ceramic and silicon (or, silicon coated with Si_3N_4 or SiC), they are resistant to corrosion, and generate virtually no particles.

The devices are created from modular components. The science and technology of these components will be detailed. The modules examined are: normally-open proportional valves; normally-closed, low leak-rate shut-off valves; critical orifices (to extract information of flow rate); flow models (to extract flow rate from pressure and temperature information); silicon-based pressure sensors; and, the precision ceramic-based packages which integrate these modules into useful devices for semiconductor processing.

The work finishes with a detailed description of the low-flow mass flow controller.

List of Symbols and Variables

dV_F, V_o	Volumetric change and initial volume of Fluorinert
β	Temperature coefficient of expansion of Fluorinert liquid
T_{FC}, T_{fill}	Mean and fill temperatures of Fluorinert liquid
s, a	Membrane stroke (or, membrane-to-NO-orifice gap) and radius
h, t	Membrane, cavity thickness
P	Pressure differential across the membrane
E, μ	Young's modulus (190,000 MPa) and Poisson's ratio (0.09) for silicon
σ	Membrane stress
$\dot{m}$	Mass flow (typically in sccm, normalized to the STP flow at 273 K)
P_{in}, P_{out}, P_x	Inlet, outlet, intermediate (pressure sensor) pressures
v, K	Flow velocity, loss coefficient
γ	Ratio of specific heats, c_p / c_v
α	$=\sqrt{\gamma\left(\frac{2}{1+\gamma}\right)^{\frac{\gamma+1}{\gamma-1}}}$
δ	$=\sqrt{\frac{4\gamma}{(\gamma+1)(\gamma-1)}}$
R	Gas constant in $p=\rho RT$ (8314 m^2/K-sec^2 divided by mol. wt.)
ρ	Gas density
D (or d), A, C_d	Diameter, area, and coefficient of discharge for an orifice

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Introduction

The present and future requirements of the semiconductor industry for gas distribution and control are well documented [1,2]. The arrival of facilities to fabricate 300 mm silicon wafers creates opportunities for new technologies to meet the challenging performance, cost, yield, and reliability specifications for devices manufactured in these facilities.

The gas control and distribution portions of these facilities will be faced with particular challenges. Particles must be reduced in size and number. This reduction requires: increased materials compatibility with process gases; decreased dead space volumes; decreased numbers of, or improved welds; and decreased numbers of, or improved, face seals.

Several conventional means to meet these challenges have been proposed [3]. Approaches based on microelectromechanical systems (MEMS) [4] offer numerous advantages. Materials in silicon-based microvalves and microfluidic systems are compatible with a wide range of electronics specialty gases (ESG). Where the gas in question is corrosive to silicon, thin film coatings such as SiC and Si_3N_4 may be used to coat the wetted surfaces and restore corrosion resistance [5]. Decreased dead volumes have already been demonstrated in micro chemical analysis systems [6]. Laboratory versions of MEMS-based electrostatic microvalves have been reported [7].

In this work, we report the use of our MEMS-based thermopneumatic valve, pressure regulator, and mass flow control (MFC) technologies [8] to create ultraclean, integrated gas sticks, pressure regulators, shut-off valves, and mass flow controllers for ESG distribution. The use of MEMS components and modules minimizes, or eliminates altogether, the size and number of welds and face seals used in integrated gas control and distribution components. Dead space volumes and wetted surface areas are reduced dramatically. When combined with the use of materials compatible with ESG, the generation of particles leading to product defects is also greatly reduced.

This paper first describes the MEMS-based modules used to achieve ultraclean gas control and distribution devices for ESG applications. The devices themselves are next described. A detailed description of one of these devices, a low-flow mass flow controller for He backside wafer cooling, and for control of low-flow, critical processes, completes our discussion.

MEMS Modules

In order to create a true system, MEMS-based devices require a number of modules. The modules utilized in our gas control and distribution devices include: the underlying flow model (supported by the electronics); critical flow orifices; normally-open proportional valves; normally-closed, low-leakage shut-off valves; temperature and pressure sensors; and the advanced ceramic packages which combine the modules into higher-level devices.

Flow Models

The design of gas control devices begins with the models for flow [9]. More complicated equations are used in the actual design, to incorporate (for instance) temperature dependencies, or fluidic resistances along the overall flow path. For purposes of this work, we focus on the descriptions of the flow of ideal gases through beveled orifices with an ideal coefficient of discharge. The expressions for the flow can then be broken into subsonic and sonic (or choked) flow regimes. The expression for subsonic flow is:

$$\dot{m} = \frac{P_{in}}{\sqrt{RT}} C_d A \left(\frac{P_{out}}{P_{in}} \right)^{1/\gamma} \delta(\gamma) \sqrt{\left(\frac{P_{in}}{P_{out}} \right)^{\frac{\gamma-1}{\gamma}} - 1} \qquad (1)$$

while the expression for sonic flow is:

$$\dot{m} = P_{in} C_d A \frac{\alpha(\gamma)}{\sqrt{RT}} \qquad (2)$$

In instances where either sonic or subsonic flow is allowed in a control device, two pressure sensors are required on either side of a critical orifice (see Figure 9), in order to extract the measured flow. In many applications, however, the outlet pressures are on the order of 10-200 Torr, allowing sonic flow to be assumed, and enabling the use of a single pressure sensor. Typically, the inlet pressure must exceed the outlet pressure by a factor of 2, to ensure sonic flow conditions, although this factor is gas-dependent.

The control electronics manage the relationship between pressure and temperature sensors, and power input to the various valves in the flow control and distribution devices. For instance, in the low-flow MFC device described later, pressure and temperature sensors near the critical orifice are used with Equation (2) to extract the mass flow rate. Depending upon the mass flow set point for the device, the electronics provide the feedback control to the normally-open proportional valve, in order to match the flow rate with the set point, within the accuracy and resolution specifications.

For normally-open valves, where the flow through an inlet impinges on the valve membrane, an alternative approach is to describe the flow in terms of a loss coefficient K, defined as $K \equiv \Delta P / (\rho_{in} v^2 / 2)$. If the mass flux is expressed as $\dot{m} = \rho A v$, then the flow (regardless of sonic or subsonic regime) can be expressed as:

$$\dot{m} = A \sqrt{\frac{2}{K} \rho_{in} (P_{in} - P_{out})} \qquad (3)$$

In this instance, the expression for our measured loss coefficients, for impingement flow, is:

$$K = 241.23 \cdot \exp\left(-\frac{z/d}{0.027}\right) + 5.854 \cdot \exp\left(-\frac{z/d}{0.546}\right) \qquad (4)$$

where z is the distance between the valve membrane and the valve inlet orifice at full-open flow, and d is the hydraulic diameter of the valve inlet.

Critical Flow Orifices

The critical orifices used in our devices are fabricated using silicon micromachining technology in our fabrication facility. Conventional, wet anisotropic etching is used to create the sharp, beveled orifices required for Equation (2) to hold.

Resolution is closely tied to the size of the critical orifice. Figure 1 shows the nature of this relationship. The results assume He flow associated with a low-flow MFC. The inlet and outlet pressures are assumed to be 30 psia and 100 Torr, respectively. The pressure sensor electronics are assumed to have 12 bits of analog to digital conversion in the sensing path, of which 2 bits may be 'lost' to noise. The flow model of Equation (2) is assumed. For example, if a 0.01 sccm He flow resolution is desired, and the minimum pressure resolution is 0.03 psia, then the critical orifice's linear dimension must be less than 15 μm.

Normally Open Valve

Normally-open (NO) proportional control valves using thermopneumatic actuation have been reported since 1986 [10]. Recently, use of these valves has been extended to include control of liquids, over wide ranges of temperature and pressure [11]. Figure 2 shows a cross-section of an NO proportional control valve. The fabrication process has been described elsewhere [11], but relies on both silicon fusion bonding [12], and silicon-to-Pyrex anodic bonding [13]. Since the valve is surface mounted, no Pyrex is exposed to the fluid traversing the valve. Typical dimensions are: 6.0 x 6.3 mm^2 lateral dimension; 0.8 mm thick Pyrex; 0.4 mm thick membrane layer, with 50 μm thick membrane; 0.4 mm thick orifice layer; 25-500 μm orifice.

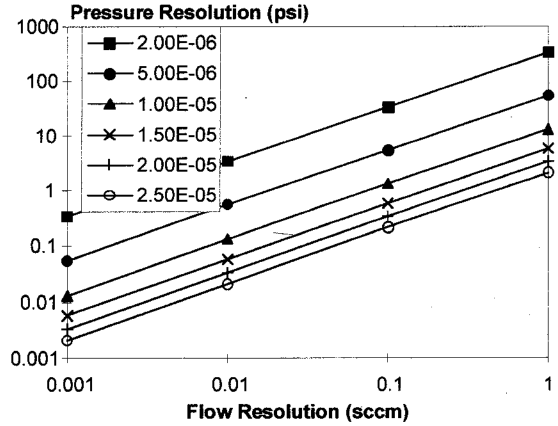


Figure 1: Pressure sensor resolution required to achieve a given flow resolution, as a function of critical orifice dimension (m).

The thermopneumatic actuation principle relies on a hermetically sealed cavity, which is filled with Fluorinert™ (FC). The cavity incorporates a platinum resistor, to provide controlled heat transfer to the FC liquid. The cavity is rigid on five of its six sides. The sixth side is comprised of a flexible, single-crystal silicon membrane. Heating the FC liquid causes it to expand. The membrane moves in response to this expansion, and ultimately forms a seal with the valve seat, which is also comprised of silicon.

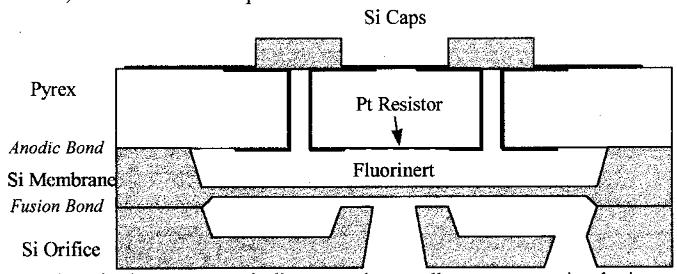


Figure 2: Cross-section of a thermopneumatically-actuated, normally-open, proportional microvalve. The inlet (center hole) is the smallest of the two holes.

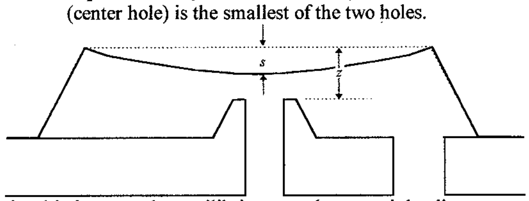


Figure 3: Relationship between the equilibrium membrane-to-inlet distance z and the stroke s.

Figure 3 shows a schematic representation of the membrane deformation, related to the variables in the following equations. The behavior of the NO device is described in [8]. Additional descriptions for the behavior of single-crystal silicon membranes may be found in [14]. In terms of describing the behavior of the device, the following equations provide the most immediate insight. Equation (5) describes the change in volume in the sealed cavity, as a function of the coefficient of thermal expansion of the FC liquid, fill temperature of the liquid, and mean temperature of the liquid:

$$dV_F = V_0 * \beta * (T_{FC} - T_{fill}) \quad (5)$$

The change in cavity volume is also related to the geometrical shape of the membrane as it deforms. If the membrane is assumed to be circular:

$$dV_F = \frac{1}{6}\pi s(3a^2 + s^2) \quad (6)$$

These expressions create a relationship between the membrane stroke s (the departure from its equilibrium position z), and the power input to the valve as defined by the mean FC temperature T.

The stroke s may also be considered as a response to P, the transmembrane pressure:

$$s = 0.0151 \cdot (1-\mu^2) \cdot \frac{Pa^4}{Eh^3} \quad (7)$$

Simultaneously, the deformation of the membrane creates stress in the silicon:

$$s = 0.0491 \cdot (1-\mu^2) \cdot \sigma \cdot \frac{a^2}{Eh} \quad (8)$$

From a design perspective, then, an NO valve must meet the ambient temperature specifications, while closing against the specified system pressures, while minimizing the power consumption, and staying well below the fracture strength of the crystalline silicon.

Normally Closed Shut-off Valve

Normally-closed (NC) valves are important components of other MEMS-based microvalve devices [15]. We report here the development of NC valves which have a wetted path which is entirely ceramic (Al_2O_3) or silicon. These valves also have incorporated a proprietary sealing technology, which enables very low leak rates to be obtained [16]. As with the NO valve modules, wetted surfaces may be coated with SiC or Si_3N_4, in order to provide materials compatibility in situations where a wetted silicon surface would be undesirable.

Figure 4 shows a cross-section of this normally-closed, low-leakage shut-off valve. The thermopneumatic actuation principle is still employed. In this case, however, a boss is added to the silicon membrane, and a silicon cantilever is fusion-bonded to the boss. Under conditions of zero input power, this cantilever will provide the shut-off property by sealing against a low-leakage seat. As shown, the wetted path is entirely silicon or ESG-compatible ceramic. The silicon-ceramic interface is a eutectic bond. The overall dimensions are 8 mm x 6 mm x 2 mm, and are (roughly) to scale.

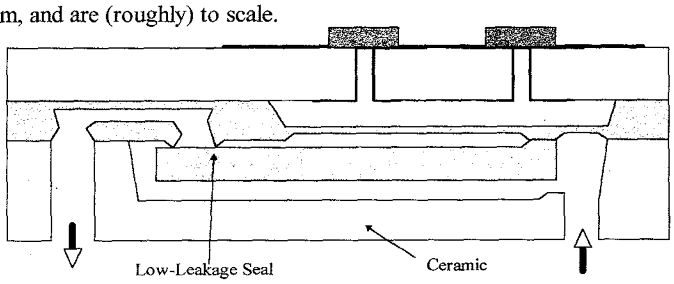


Figure 4: Cross-section of a thermopneumatically-actuated, normally-closed, low-leakage shut-off valve.

Figure 5 shows measured helium leak rates for a set of microvalves. The sealing material in these devices is Viton; we are in the process of characterizing seals made with other materials, such as Kel-F and Kelrez. Also shown is data from a standard shut-off valve commonly used in the industry. The SEMATECH specification for shut-off valves is less than 10^{-9} cc-He/sec after 15 seconds of shut-off. Shut-off valves used at present in the industry reach higher steady-state leak rates than these microvalves, due to their more permeable sealing materials, or smaller compression forces on the sealing surfaces. At the same time, the width of their sealing surfaces is greater than in our microvalve, occasionally resulting in lower metastable values of leak rate.

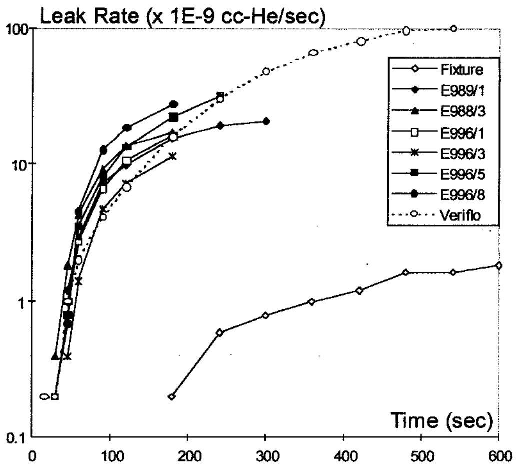


Figure 5: Helium leak rate for vacuum leak-rate shut-off microvalves.

Sensors (Pressure, Temperature)

In our present devices, small (several millimeters square) temperature sensors and piezoresistive pressure sensors are used to monitor temperature and pressure in the device flow path. These sensors are commercially available. When incorporated into a final flow control device, the information they provide becomes the basis for the temperature and pressure calibration data which is stored on E^2PROM. It is important that sensing occur as close as possible to the flow point of interest. For instance, in a low-flow MFC, the pressure must be sensed as close as possible to the inlet of the critical orifice.

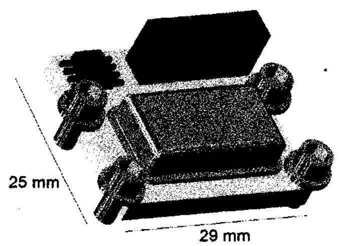


Figure 6: Example isometric view of a pressure regulator, MFC, or shut-off valve.

Advanced Ceramic Packaging

Ceramics available as a result of advances in semiconductor integrated circuits have the structural and materials properties required for application to ESG delivery and control. Figure 6 extends the cross-section of Figure 3, and shows an isometric view of the use of such ceramics for pressure regulation, mass flow control, or low-leakage shut-off applications. The ceramics allow integration of an E^2PROM, which holds the calibration constants for the particular device, as well as constants for a variety of gases. A metal lid provides a hermetic seal for the valve modules, and the pressure and temperature sensing modules. Electronic control signals are communicated via metal lines patterned on the ceramic surface.

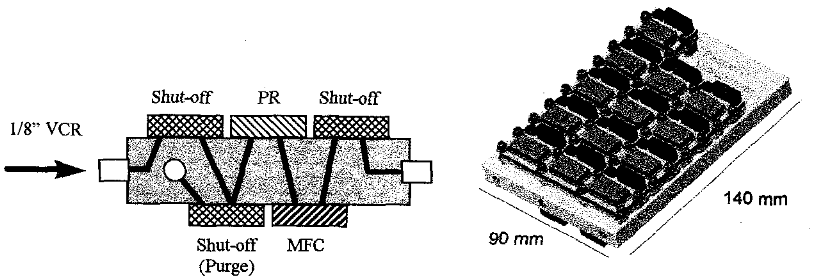
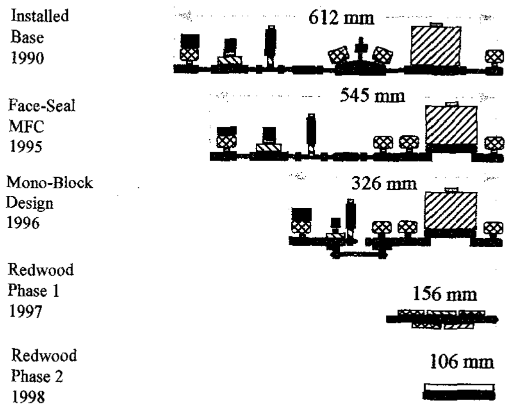


Figure 7: left) Schematic of the integrated gas stick; right) Isometric view of a 4-channel gas stick.



	# of Welds	# of Seals	Internal Volume
1990	10	0	38 cc
1995	6	8	31 cc
1996	3	12	22 cc
1997	0	10	2 cc
1998	0	0	<1 cc

Figure 8: Size comparison of present and future integrated gas sticks/panels (after [3]).

Gas Distribution Devices

These MEMS-based modules can be combined to create a hierarchy of gas control and distribution devices. Some of these devices, such as the pressure regulator or the MFC, can themselves be used to build still higher levels of functionality, in the form of, for instance, a fully integrated, multiple-channel gas panel.

Figure 7 shows the schematic and isometric views of a fully-integrated gas panel, comprised of four single-channel gas sticks. The manifold on which the individual modules reside is typically built from stainless steel. The size of this gas panel compares very favorably to existing designs. As shown in Figure 8, existing panels with identical functionality occupy ten times the area of 1995 panel designs, and over four times the area of 1996 designs.

Low-Flow Mass Flow Controller

As an example of an integrated flow this device, which uses pressure-based flow sensing distribution and control device, we will as described in this work. Table I gives a sample focus upon a low-flow mass flow specification. The flow range and resolution is set controller. Figure 9 shows a schematic of by the critical orifice, as depicted in Figure 1.

Fluid Media:	Corrosive Gases and Liquids
Maximum Flow Rates:	1, 10 sccm (N2 at 20 psid)
Turndown Ratio:	10:1
Accuracy:	• 1% of F.S.
Repeatability:	• 0.2% of F.S.
Resolution:	0.1 sccm
Response Time:	500 ms typical
Valve Leak Rate:	5 x 10^{6} cc/sec He
Inlet Pressure Range:	0 to 50 psig
Maximum Outlet Pressure:	10 Torr
Temperature Range:	0 to 50°C
Power Consumption:	3.5 W typical
Dimensions:	106 mm x 40 mm x 25 mm

Table I: Specification for low flow MFC.

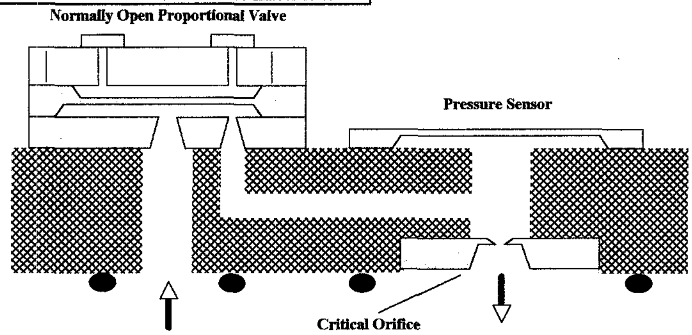


Figure 9: Schematic representation of the low-flow MFC.

Principles of Operation

Using the flow models shown earlier (Equations 1-2), it is possible to model the behavior of the low-flow MFC. A series combination of a critical orifice (CO) and normally-open valve (NO) is the simplest device-level flow model, as shown in Figure 10. The NO orifice area is, in effect, set by of the walls of a cylindrical tube:

$$A_{NO} = \pi D_{NO}(z - s) \tag{8}$$

P_x represents the pressure to be sensed by the pressure sensor, which will be fed back into the electronics in order to control the NO valve. As opposed to the models of Equations 3-4, this flow model assumes isentropic flow of a compressible gas. That is, no losses due to energy lost via friction or work (momentum changes) are considered.

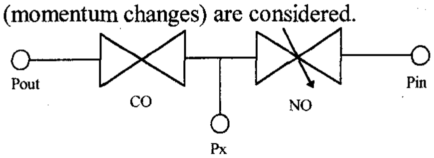


Figure 10: Schematic representation of the compressible flow model for the series combination of a normally-open proportional valve, and a critical orifice

Figure 11 shows an example of the output of the flow model, and the measurements from a completed MFC. The left-hand figure shows the flow through the NO and CO, as a function of the pressure sensor pressure. The intersection of the NO and CO curves determines the value of the pressure P_x, as a function of the membrane-to-inlet gap z-s. Using Equation 2, this pressure also determines the mass flow. When the NO valve is unpowered, the membrane-to-inlet gap is the full value z, and very little pressure is dropped across the NO valve. As s increases, more pressure is dropped across the NO, and the flow decreases. Power input to the NO valve, (the signal voltage applied in the right-hand figure) is responsible for increasing s (see Equations 5-6), and decreasing the membrane-to-inlet gap.

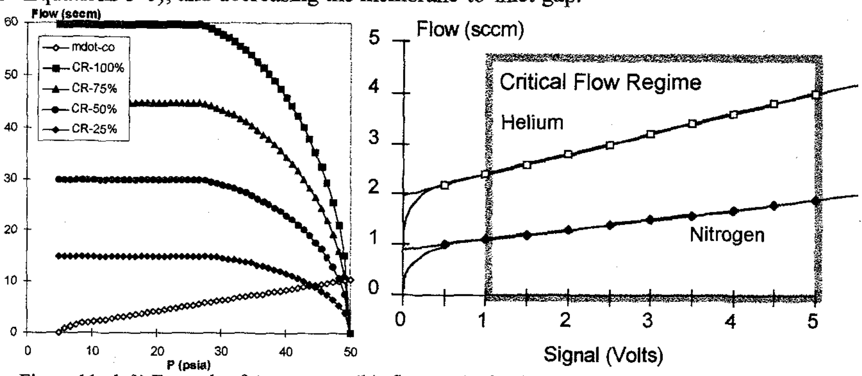


Figure 11: left) Example of the compressible flow model for the low-flow MFC; right) measured flow characteristics for a low-flow MFC

Control of the mass flow is effected by comparing the flow determined from the pressure sensor measurement, and comparing it to a set point. If the flow is too high compared to the set point, additional power is sent to the NO valve, increasing s, and decreasing the MFC flow. If the flow is too low, the power input to the NO valve is decreased, causing s to decrease back toward the unpowered value z. Temperature-dependent information, compensating for temperature-induced package stresses on the pressure sensor, and temperature-related changes in flow in Equation 2, are stored in an E^2PROM on the MFC module (see Figure 6).

Conclusions

We have demonstrated the science and technology required to design and fabricate flow distribution and control devices suitable for the semiconductor processing industry. Components such as pressure-based flow models, critical orifices, pressure and temperature sensors, normally-open proportional valves, and normally-closed vacuum leak rate shut-off valves, have developed. The valve actuation is based on previously developed thermopneumatic techniques. These components have been integrated into shut-off valve, mass flow controller, and pressure regulator modules, which themselves are combined at a higher level into integrated gas panels. Each integrated device has the benefit of small size, lower cost, higher resolution, materials compatibility, and lowered defect generation, which are among the attributes of the successful application of MEMS-based technology.

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