RELIABILITY OF MEMS-BASED MASS-FLOW CONTROLLERS FOR SEMICONDUCTOR PROCESSING

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ABSTRACT

Microfabricated components are finding increasing application in semiconductor processing. In this work, we report the results of detailed reliability and MTTF studies on mass-flow controllers (MFCs) created from silicon pressure sensors, microfabricated orifices for use in the flow sensor, and microvalves. Attributes studied include accuracy, response time, inboard leak rate, and particle generation, all monitored versus number of cycles. From these measurements, MTTF is calculated to be greater than 3M cycles. Failure modes are also discussed in detail. [*Keywords:* MEMS; silicon microvalves; silicon pressure sensors; mass-flow control; MFC; reliability; MTTF.]

INTRODUCTION

The use of MEMS-based devices is becoming increasingly common. Pressure sensors [1] and accelerometers [2] for automotive applications, and ink-jet printheads for printing applications [3], are arguably the highest-volume MEMS devices in production. Despite these applications, reports on reliability of such devices in the archival literature have been relatively few.

In this work, we report detailed reliability and mean-time-to-fail (MTTF) studies of MEMS-based mass-flow controllers (MFCs). The primary intended use for these MFCs is high-performance and high-purity control and distribution of gases, used in the processing of semiconductor integrated circuits and similar microfabricated devices [4].

Eleven MFCs were characterized for reliability according to semiconductor equipment standards. Parameters considered important to semiconductor processing were measured to specifications at regular intervals during the reliability cycling.

MEMS-BASED MFCs

Figure 1 depicts schematically the MEMS-based MFCs studied in this work. The MFC is comprised of a flow sensor, a microvalve to throttle flow, and feedback electronics to maintain the flow relative to a user-commanded setpoint. The flow sensor is comprised of a silicon micromachined orifice, a silicon IC temperature sensor, and two silicon piezoresistive pressure sensors. Calibration information relating the pressure sensor outputs to the actual flow under a variety of setpoint, inlet pressure, and temperature conditions, is stored on-board the MFC. Full details of this device are reported elsewhere [4]. For this study, the maximum (full-scale) flow rate of the MFCs was 100 standard cubic centimeter per minute (sccm), nitrogen-equivalent for seven MFCs (serial numbers 1382 through 1388) and 200 sccm for four MFCs (serial numbers 1284, 1285, 1286, 1288). Full scale is referenced to the maximum flow of the MFC.

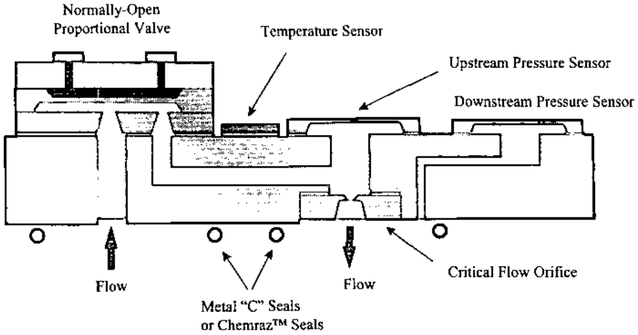

FIGURE 1A. SCHEMATIC CROSS-SECTION OF THE MEMS-BASED MFCs USED IN THIS STUDY.

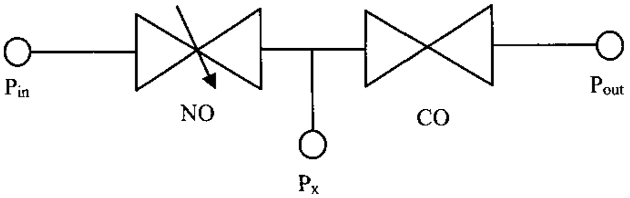

FIGURE 1B. FUNCTIONAL SCHEMATIC OF THE MEMS-BASED MFCs USED IN THIS STUDY. 'NO' IS THE NORMALLY-OPEN SILICON MICROVALVE. 'CO' IS A SILICON-MICROFABRICATED ORIFICE, TYPICALLY OPERATING IN THE CRITICAL (SONIC) FLOW REGIME. 'P_X' IS THE UPSTREAM PRESSURE SENSOR, AND 'P_{OUT}' IS THE DOWNSTREAM PRESSURE SENSOR.

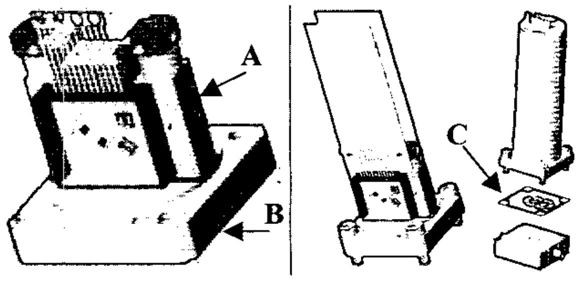

FIGURE 1C. CUT-AWAY DRAWING OF A PACKAGED MFC AND PROGRESSIVE ASSEMBLY INTO FINAL PACKAGE (A IS THE CENTERLEG, B IS THE BASE, C IS THE SEAL PLATE).

TEST PROTOCOLS AND SPECIFICATIONS

Protocols for testing of MFCs are well-established, published, and maintained by SEMI and SEMATECH [5]. For this study, each MFC had its setpoint cycled according to the protocol specified by SEMI E67 and SEMASPEC 92071224. The setpoint of the MFC is the input signal (commanded) expressed as percentage of full scale flow or sccm. The protocol required cycling through setpoints 100-

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25-75-0% repeated. Each setpoint was applied for 1.25 seconds. One cycle is defined as 2.5 seconds. Figure 2 describes the cycling:

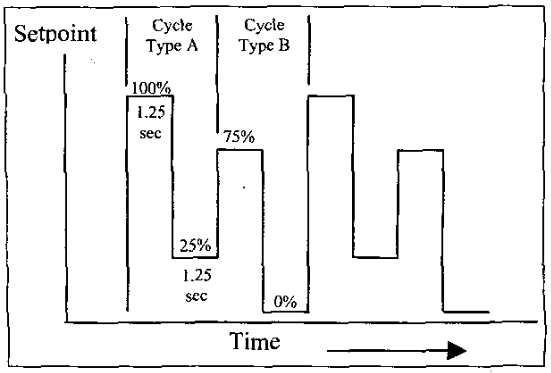

FIGURE 2. CYCLING DESCRIPTION, BASED ON SEMI E67 [5].

Readouts of parametric performance were made every 250K cycles starting at 0 cycles, with an additional readout at 100K cycles. Parameters monitored were particle generation, accuracy of the flow, linearity, response time, zero offset, through-valve leak rate at zero setpoint, and inboard vacuum leak rate of the overall MFC structure.

The data for accuracy, linearity, zero offset, and valve leak across the seat were collected during the same test. Accuracy and linearity were based on flow measurements at different setpoints and calculated according to SEMI E56. SEMI E56 defines accuracy of the flow to include both precision and bias. Zero offset is the indicated flow of the MFC at a no flow condition expressed in millivolts. The indicated flow is the electrical output of the MFC, expressed in either voltage or sccm. In voltage, the range is 0 to 5 volts. Linearity measures how close the flow values fit a straight line. The straight line is based on the measured flow at 100% of full scale (%FS) and the zero offset. Response time is defined in SEMI E17 as the time between the commanded setpoint change and when the measured flow first enters the specified band. The specified band is ±2% of the final steady value or ±0.5% of full scale, whichever is greater. [5]

Table 1 describes the parametric tests and specifications. The testing was performed in the sequence as listed in the table. The equipment used for the measurements met the requirements from the standards listed in Table 1. A condensation particle counter model 3010 manufactured by TSI was used for the particle measurements. This particle counter counts particles in the size range of 10 nm to 1 μm. Accuracy, linearity, and valve leak across the seat were measured with a DH Instruments Molbox1 system. This system measures flow and the flow accuracy is NIST Traceable to 0.02% of full scale or 0.2% of setpoint, whichever is greater. Zero offset is based on the analog output of the MFC in voltage and measured with a Keithley digital multimeter model 2000. Response time measurements were measured with a Honeywell flow sensor model AWM 3100V, which has a maximum response time of 3 milliseconds. The inboard leak was measured with a Varian model 979D helium leak detector, which has 2 X 10^{-12} atm cc/sec helium sensitivity.

TABLE 1. PARAMETRIC TESTS INFORMATION (ALL TESTS PERFORMED AT 20-25°C AMBIENT.) NOTE: %FS = %Full Scale.

Parametric Test	Units	Specification	Standard
Particle (Cycle test)	Particles per cycle	≤ 0.01 particles per cycle larger than 0.01 micron after 120 minute clean up period as measured over 500 cycles	SEMASPEC 92071226-STD
Accuracy	%FS	≤ ±1% of the full scale rated flow from 5% to 100% of the rated flow	SEMI E56, SEMASPEC 92071221-STD
Linearity	%FS	≤ ±1% of the full scale rated flow from 5% to 100% of the rated flow	SEMI E56, SEMASPEC 92071221-STD
Zero Offset	mV	≤ ±25 mV	SEMI E56, SEMASPEC 92071221-STD
Valve Leak Across the Seat	%FS	≤1% of full scale rated flow	SEMI E56, SEMASPEC 92071221-STD
Response	seconds	≤1.25 seconds	SEMI E17
Inboard Leak	Atmosphere (atm) cc/sec He	≤ 1 X 10^{-9} atm cc/sec He	SEMI E16

RESULTS

Figures 3 through 9 show the results for particle generation, accuracy, linearity, zero offset, through-valve leak rate, response time, and inboard (package) vacuum (helium) leak rate, all as a function of the number cycles. Accuracy, linearity, and time response show the worst case values, since multiple measurements were taken.

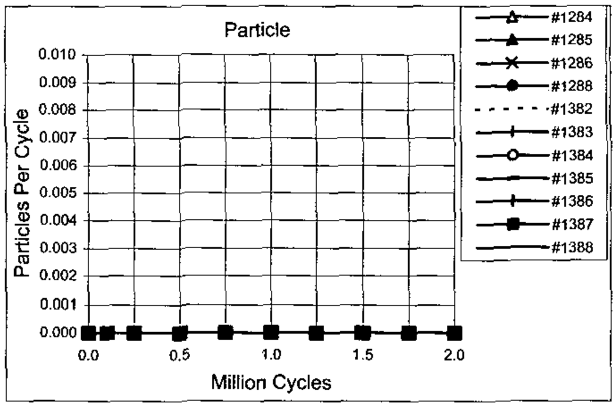

FIGURE 3. PARTICLE OVER CYCLING (SPECIFICATION: < 0.01 PARTICLES PER CYCLE).

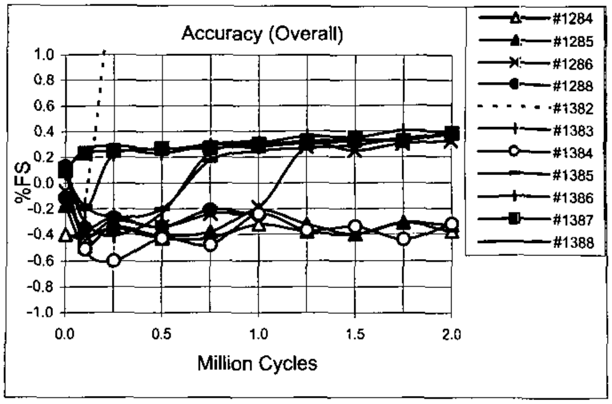

FIGURE 4. OVERALL ACCURACY OVER CYCLING FOR SETPOINTS FROM 5% TO 100% OF FULL SCALE (SPECIFICATION: < 1% FS).

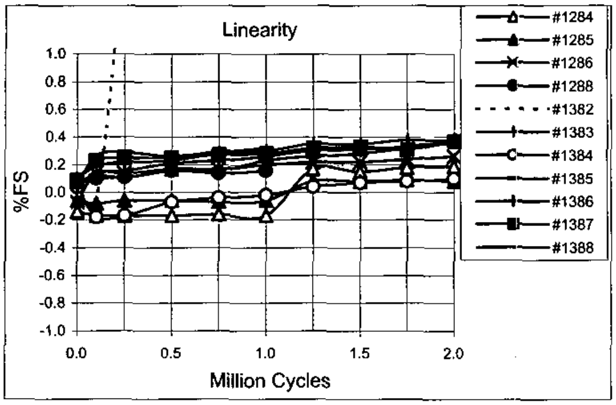

FIGURE 5. LINEARITY OVER CYCLING FOR SETPOINTS FROM 5% TO 100% OF FULL SCALE (SPECIFICATION: < 1% FS).

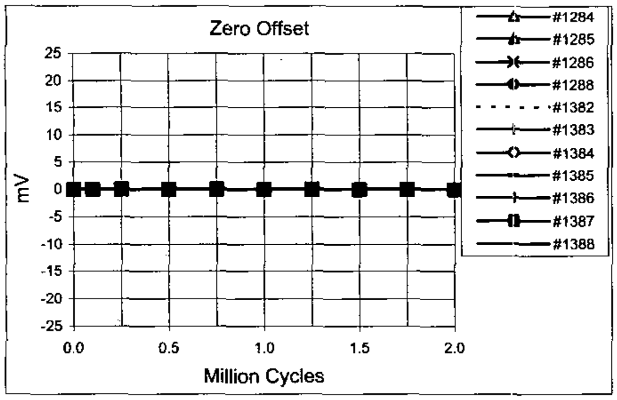

FIGURE 6. ZERO OFFSET OVER CYCLING (SPECIFICATION: < 25 MV).

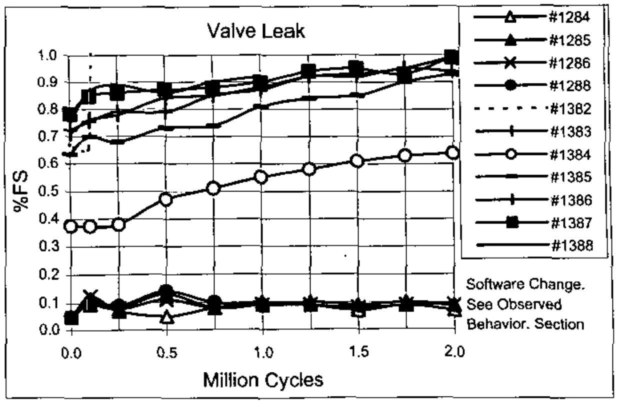

FIGURE 7. THROUGH-THE-VALVE LEAK RATE FOR 0% SETPOINT COMMAND (SPECIFICATION: <1% FS).

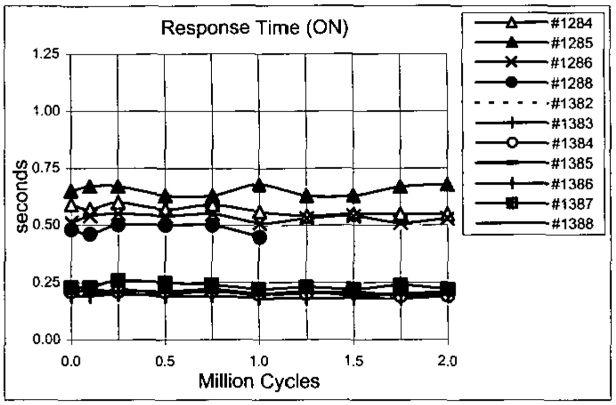

FIGURE 8. WORST-CASE SETPOINT TRANSITION RESPONSE TIME (SPECIFICATION: < 1.25 SEC).

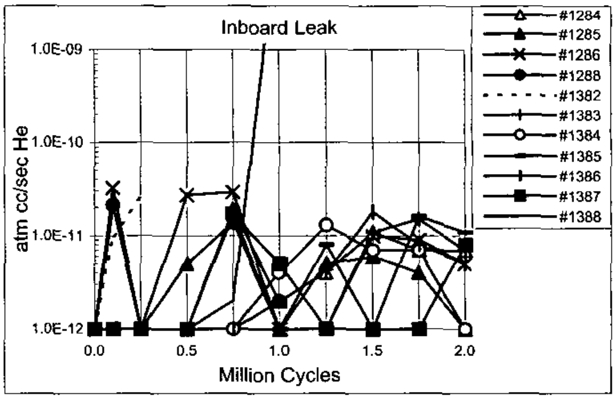

FIGURE 9. INBOARD LEAK RATE OVER CYCLING (SPECIFICATION: < 10^{-9} ATM-CC HE/SEC).

Accuracy and linearity values were measured at the following setpoints: 5, 10, 20, 30, 40, 50, 60, 70, 80, 90, and 100% according to the SEMI E56 protocol, where numerous measurements were taken and averaged. Figures 4 and 5 show the values at the setpoints that had the maximum (absolute) accuracies. Figures 10 and 11 show the accuracy and linearity for one representative unit, #1387 as a function of setpoint.

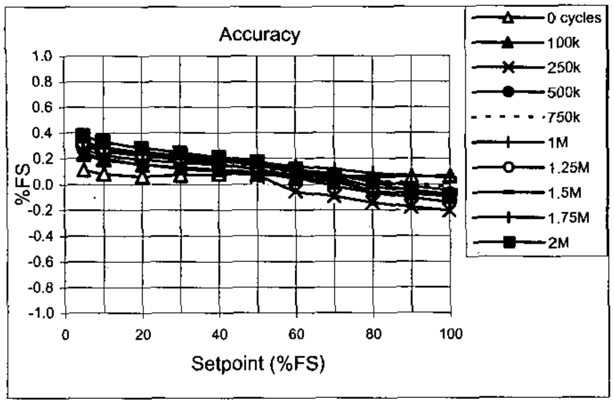

FIGURE 10. ACCURACY FOR #1387 (REPRESENTATIVE MFC) FOR SETPOINTS FROM 5% TO 100% OF FULL SCALE (SPECIFICATION: < 1% FS).

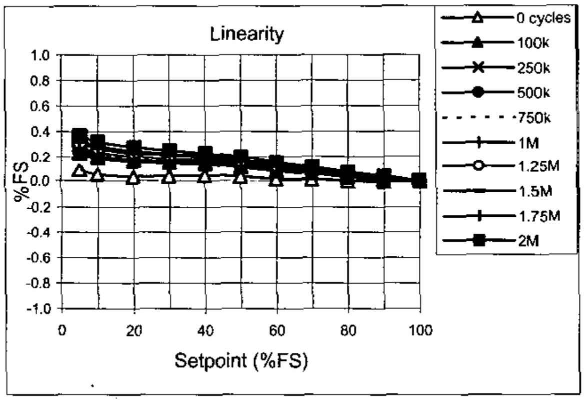

FIGURE 11. LINEARITY FOR #1387 (REPRESENTATIVE MFC) FOR SETPOINTS FROM 5% TO 100% OF FULL SCALE (SPECIFICATION: < 1% FS).

Figure 8 shows the worst-case values for response time. Response times were measured for four different setpoint changes as SEMI E17 specifies. The four different setpoint changes are 1% to 100%, 1% to 25%, 25% to 75%, and 75% to 25%. Table 2 shows the complete response time results for the different setpoint changes for a representative MFC, #1387.

TABLE 2. TIME RESPONSE RESULTS IN SECONDS FOR #1387, A REPRESENTATIVE MFC (SPECIFICATION < 1.25 SECONDS)

# Cycles	1% to 100% Setpoint (seconds)	1% to 25% Setpoint (seconds)	25% to 75% Setpoint (seconds)	75% to 25% Setpoint (seconds)
0	0.23	0.13	0.10	0.11
100 K	0.23	0.12	0.09	0.11
250 K	0.26	0.13	0.11	0.10
500 K	0.25	0.13	0.10	0.10
750 K	0.24	0.13	0.10	0.06
1 M	0.22	0.12	0.09	0.07
1.25 M	0.23	0.12	0.10	0.06
1.5 M	0.22	0.12	0.09	0.06
1.75 M	0.24	0.13	0.10	0.06
2 M	0.22	0.11	0.09	0.06

MTTF CALCULATION

Eight devices were tested and passed through 2M cycles. One device was tested and passed through 1M cycles (and not tested further to failure). Two failures occurred in this characterization. A failure in this testing is defined as not meeting any one of the specifications in Table 1. One MFC failed at 1M cycles for inboard leak rate. One MFC failed at 250K cycles for closing (through-valve leak rate). This failure affects the accuracy and linearity readings but the failure is counted for valve leak rate.

The mean time to failure (MTTF) calculation assumed a 90% confidence and an exponential hazard function [6]:

$$\mathrm{MTTF} = 2T/\chi^2 = 3.35\mathrm{M\ cycles}$$

Where:
T is the total number of passing cycles.
$T = 2{,}000{,}000{*}(8) + 1{,}000{,}000{*}(1) + 100{,}000\ (1) + 750{,}000\ (1)$
(The last known passing intervals for the two failures are 100,000 and 750,000.)

χ^2 is a statistic that is a function of the confidence level (α) and degrees of freedom ($2r+2$).
$\chi^2 = 10.64$ for $\alpha = 0.9$ confidence, $r = 2$ failures

OBSERVED BEHAVIOR, FAILURES, AND ANALYSIS

Particles generated were less than 0.005 particles per cycle, in the size detection range of 10 nm to 1 µm (i.e., below the rate detection limit of the condensation nucleation counter). Zero offset changes were less than 0.1 mV. Response time values remained in specification and did not show any change as a function of cycling. The four 200 sccm MFCs were slower overall because they were manufactured for a wider dynamic range of 80:1 for "multirange" performance testing. The other MFCs were manufactured for a 20:1 dynamic range. For the thermopneumatically-actuated microvalves used in these MFCs, it is possible to trade-off response time against dynamic range [7].

One MFC (#1388) failed for inboard leak and was examined. The helium leak occurred at the 'C' seal interface between the base block and the MFC package (see Figure 1c). Replacement of the 'C' seal eliminated the failure. One cause for this failure type could be handling, but this model type was shown to pass both shock and vibration in November 2001 to MIL STD 810E. Two MFCs and two MEMS integrated gas sticks were tested for shock and vibration. An integrated gas stick is equivalent to a gas stick with a pressure sensor, regulator, upstream shut-off valve, MFC, and downstream shut-off valve.

The details on the vibration and shock characterization performed in 2001 are as follows. Vibration was performed on three axes and equivalent to 3000 miles of truck transportation on each axis. The acceleration was 1.010 G_{rms} on each axis. Shock was performed on three axes, at 9 milliseconds, sawtooth form, 40 Gs. An additional 9 millisecond, ½ sine form, 40 G shock was performed on the horizontal axis of each unit. The units were evaluated for accuracy, linearity, MFC valve leak across the seat, inboard leak, and particles before and after shock and vibration testing. The units passed all testing and Table 3 summarizes the results.

TABLE 3. SUMMARY OF PREVIOUS SHOCK AND VIBRATION RESULTS, MAXIMUM VALUE OF PRE AND POST TESTING LISTED.

Parametric Test	Specification	IGS 1273	MFC 1274	MFC 1275	IGS 1276
Inboard Leak (atm cc/sec He)	$\leq 1 \times 10^{-9}$	1.3×10^{-10}	$\leq 1 \times 10^{-10}$	4.0×10^{-10}	6.2×10^{-10}
Particle (particle per cubic foot)	75	8	5	0	4
Accuracy (%FS)	1	0.37	0.40	0.03	0.34
Linearity (%FS)	1	0.04	0.10	0.06	0.15
MFC Valve Leak (%FS)	1	0.81	0.88	0.82	0.88

A more likely cause of the inboard leak failure is some type of package relaxation. The supplier of the manifold recommends a different bolt type, material A286, than used in the tested devices. RMI tested this bolt and it is stronger. However the torque was checked on the failed units and found to be at the correct value; therefore the bolts did not relax. In addition, only replacing the bolts while keeping the seals under pressure did not fix the leaks. The 'C' seal type used in the connection is that which is recommended by the semiconductor industry. This seal type has less 'spring' than previous 'C' seal types and may have relaxed between the centerleg and base. An additional observation upon disassembly of the failed unit was that the surface finish of the stainless steel base was brushed, and required a smoother finish to meet the specification. A combination of the surface finish on the base and the seals relaxing most likely caused the inboard leak failure.

The solution to this problem is to increase the amount of spring force in the system, rather than simply replacing the seal type with one which has more 'spring'. As previously stated, the industry recommends the seal type used and it has the best initial sealing capability. In order to increase the amount of spring force in the centerleg to base sealing system, a thinner metal plate was used to surround the seals. This causes the entire load to be on the seals, with no load on the plate surrounding the seals. The sealing surface on the base was also reworked to achieve a smoother surface. In addition, the stronger bolts were used as recommended by the manufacturer. A thermal cycling experiment was performed on test units consisting only of the module, base with reworked sealing surfaces, thinner plate, manifold, and bolts to evaluate the new system. No failures in leak rate occurred in this characterization. In addition, a group of MFCs were reassembled with the A286 bolts, reworked bases, and thinner plates. These MFCs are currently being tested for reliability.

One unit (#1382) failed for closing which also affected the accuracy and linearity results for this unit at the 250K cycle readout. It was found that the microvalve could not control flow for setpoints below 10%, and could not close the flow below 7%. It was presumed that a large particle, greater than 1 μm, prevented the valve membrane from seating fully on the valve seat.

After the 250K cycle readout, the MFC was cycled on an engineering basis for seven more days. The control system version in this unit protected against full power application for setpoints below 7%. At this level of leakage, 7% of F.S., the control system would have applied "full power" (about 2.5 watts) continuously for 1.25 seconds every 5 seconds to close the valve. In subsequent units, this protection scheme has changed to protect against applying full power at all setpoints. During the seven day cycling, the valve closing degraded to the point where the application of 1.7 watts would not close the valve below 180 sccm. The original open (unpowered) flow of the MFC was 227 sccm; the original closure was to 0.2 sccm with 1.3 watts applied. During investigation by engineering, the valve closed to 2 sccm with more power applied, 1.996 watts. This performance was "reversible": at 1.617 watts the valve opened to 236 sccm then closed back to 1.8 sccm with 2.026 watts. Increasing the power to 2.119 watts closed the valve to a leak rate of 0.1 sccm. At this point the power was reduced to 2.057 watts with a leak of 0.5 sccm. The valve was held in this condition for the next several hours. After two hours it required 2.155 watts to maintain the 0.5 sccm leak; after another 90 minutes it required 2.174 watts to achieve a 1.5 sccm leak. The valve rapidly lost ability to close. Upon disassembly and visual inspection a large bubble in the microvalve actuation cavity was observed. Since the valve still functioned and the membrane was intact, the bubble must have been introduced through a crack in the Pyrex after subsequent application of power above 2.5 watts.

This closing failure reinforces the notion that particles can interfere with closure. It is unknown when and where the assumed particle was introduced. All testing was performed with filtered high purity nitrogen. However, the MFCs had to be moved between the different test stations, which could have introduced a particle. Subsequent to this unit, a cleaning station was built to clean units. It was qualified using three MFCs, which had had closing or particle issues. In addition, SMC in Tsukuba, Japan tested ten MFCs for reliability in a Class 10 environment and found no closing failures. (The test environment at Redwood MicroSystems is Class 1000.)

Three additional points are pertinent. In practice, a DeviceNet MFC would send an "alarm" at the first incidence of not hitting the commanded setpoint. This prevents repeated cycling at maximum power. Secondly, the present valve protection algorithm limits the maximum power and time applied to the valve, such that not enough energy is available to crack the membrane or the Pyrex. Thirdly, the use of thicker Pyrex and other proprietary mitigations have been used subsequently to improve margin against this failure mode. This failure mode is not catastrophic (that is, does not lead to valve failure due to over-power condition), since the software and hardware monitors in the control system prevent the valve from being over-powered.

An additional observation was that the through-the-valve leak rate increased with the number of cycles, evident in Figure 7. Initially, MFCs are calibrated so that a 0% setpoint results in flow at less than 1% FS to meet the specification. This increasing trend is analyzed in detail in another report [7]. Briefly, however, this slow increase was found to be due to a combination of causes. First, the piezoresistive pressure sensors are operating near their resolution limit for flows less than 1% FS, so that sensor drift can cause relatively larger shifts in reported flow. Second, relaxation in either the package bolts, or in the microcomponent die attach material, or both, can cause drift in the sensor zero, leading to the observed phenomenon. Pressure sensors with improved behavior at low pressures can overcome this phenomenon [8]. This approach is important for more stringent accuracy specifications at the lower end of the operating range, where drift can also have an effect. Figure 10 illustrates this effect. At 0 cycles, accuracy is constant as a function of setpoint. As the number of cycles increases, a slope becomes evident. This slope is due to the relaxation of pressure sensor die attach. The units are within specification throughout the cycling, even though observable drift is occurring.

More practically for the listed specifications, a control scheme where a 0% setpoint controls the valve power directly, without requiring input from the pressure sensors, is also successful in virtually eliminating this long-term phenomenon. This control scheme is demonstrated with the four units in Figure 7 that are below 0.2% full scale for all cycles. These four units do not show an increasing trend in valve leak (#1284, #1285, #1286, #1288). These four units had this improved closing algorithm in place when reliability testing started for the "multirange" application referred to previously. They have an 80:1 dynamic range and were also required to close to < 0.25% FS for this application at the 0% setpoint.

CONCLUSION

Eleven MFCs intended for semiconductor processing applications were tested for reliability according to semiconductor equipment industry standards. The MFCs consist of microfabricated components. At each readout interval, each MFC was tested for particles, accuracy, linearity, zero offset, valve leak integrity (leak across valve seat), time response, and inboard leak. The MTTF was determined to be 3.35M cycles. Two failures occurred; one for inboard leak and one for closing. A solution for the leak at the 'C' seals failure type involves using the "industry standard" bolt, better surface finish on the base, and a thinner plate between the centerleg and base. Thermal cycling demonstrated that this solution works. Additional reliability testing is underway to completely test this solution. The failure to close occurrence was most likely caused by a particle as discussed; a new cleaning station has successfully cleaned other units subsequent to this failure. In addition, the current protection algorithm limits the power to the valve when it cannot close. This algorithm protects the valve from Pyrex or membrane cracking in the case where a particle is interfering with closure. Additional improvements have also been implemented in the design to make the valve stronger. The increasing trend of leak across the valve seat was due to pressure sensor drift. This problem has been solved with a different closing algorithm, as proven on four MFCs presented in this work. In addition, further developments are in process to decrease pressure sensor drift for other applications.

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