Pressure Based Mass Flow Control for Ion Implant SDS Applications

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Abstract – Thermal mass flow control (MFC) has been used to control the flow of gas in semiconductor process systems for many years. With the introduction of SDS® gas sources for ion implantation, improvements in mass flow control technology were required to maximize cylinder yield and effect a corresponding reduction in operating cost. Pressure-based MFC (PMFC) is an alternative to thermal flow control technology. Discussed are the design and operating principles of PMFC's utilizing the principal of "choked" (sonic) flow for applications with inlet pressures to below 10 torr. A comparison is made between the PMFC and thermal MFC techniques. A significant increase in throughput per bottle is presented for a device with 6 torr inlet pressure capability.

I. INTRODUCTION

Historically, thermal mass flow controllers have been used in ion implant applications to control flows less than 5 standard cubic centimeters per minute (sccm) with pressure drops of 50 torr or more. Since early 1996 [1] the SDS sub-atmospheric gas source has gained wide acceptance by the implant community. However, the large pressure drop required by the thermal MFC inhibited widespread use of SDS because significant and costly amounts of potentially usable source material remained in the bottle.

Reducing the pressure differential to approximately 10 torr results in increased utilization of source material to as much as 90%, versus 65% with a 50 torr pressure differential (Fig. 1). Both thermal and pressure based MFC technologies offer a means of reaching the lower pressure differentials. The first device reported [2] to provide this reduced pressure drop was the MKS Type 1640 PMFC.

In 1996, PMFC's were designed to operate with typical flow rates of 3 or 5 sccm full scale flow for medium or high current applications, respectively, with 12 to 15 torr inlet pressures depending on the gas. Current PMFC's are typically ranged for full scale flows of 3 to 5 sccm with inlet pressures as low as 6 torr.

II. MASS FLOW CONTROL TECHNOLOGY

Both thermal and pressure-based technologies have been used for many years for ion implant applications with high pressure gases. These devices are comprised of three major components: a measurement device, closed-loop control electronics and a proportional control valve. The valve and measurement device are the components that have the most effect on SDS source gas utilization as they directly impact the pressure drop across the device.

Most gases used in the semiconductor industry are supplied at a constant pressure, typically above atmosphere, and are delivered to a process at or below atmosphere. Ion implant gases were generally provided at a constant, regulated pressure, either from high pressure gas bottles or sublimed solids.

SDS gases are supplied at sub-atmospheric pressures that decrease as the gas is consumed. This is a critical difference for the mass flow controller, as inlet pressure, was normally constant. Changing inlet pressure can impact capability to both meter and control flow accurately, as well as achieve set-point within an allowable time.

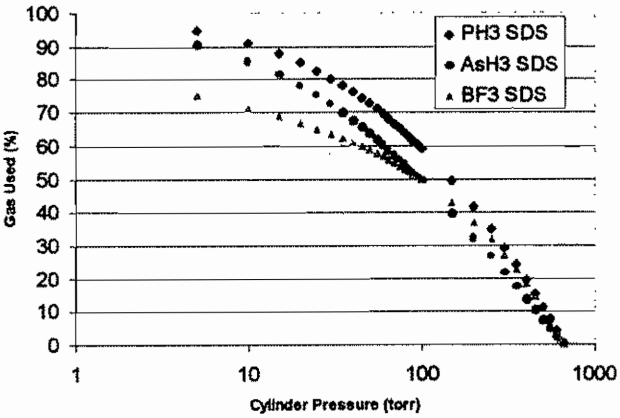

Fig. 1. SDS Gas Use Rate Efficiency

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III. PRESSURE BASED FLOW CONTROL

PMFC measurement methods include: laminar flow, critical (or sonic) flow, and molecular flow. Both molecular and laminar flow methods utilize differential pressure measurement across a flow element. The critical (or sonic) flow method, utilizes measurement and control of pressure (P1in Fig. 2) upstream of an orifice with known conductance to determine flow. Flow is proportional to P1when it is at least twice the orifice's outlet pressure (P2 in Fig. 2). P1 is controlled by adjusting the control valve position. The control electronics provides the means to open or close the valve based on an error signal generated by comparing P1 to the device set-point.

The critical flow relationship [3] is:

$Q = CP$ where,

Q = mass flow (torr - liter/second)

$$C = 28.645Co\{(\gamma T/M)[2/(\gamma+1)]^{(\gamma+1)/(\gamma-1)}\}^{0.5}a^2$$

P = absolute upstream pressure (torr)

$\gamma = Cp/Cv$, the ratio of specific heats

a = orifice radius (cm)

T = absolute temperature (K)

M = molecular weight

Co = orifice coefficient

One torr-liter per second equals 79.2 sccm.

Critical flow was chosen for the SDS application as this method provides the necessary control with minimal pressure drop. In addition, it is important to maintain the same footprint as the thermal MFC. The MKS Type 1640 PMFC utilizes the critical flow method and meets the footprint criteria. Its main components are a Type 700 Baratron® capacitance manometer, solenoid valve, critical flow orifice and control electronics (Fig. 2).

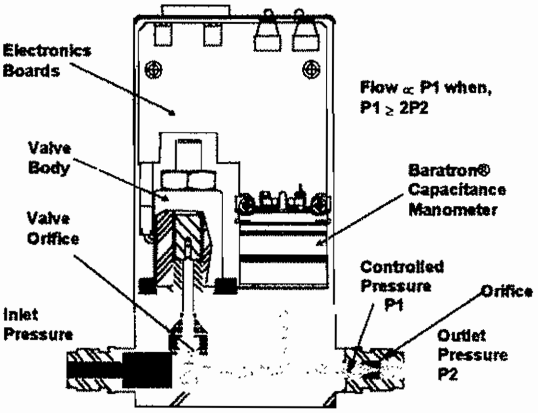

Fig. 2. Cross Section of Type 1640 PMFC

A. *Pressure Measurement*

A capacitance manometer is the optimum choice for this application as the operating inlet (SDS) pressure regime is well within the range of its measurement capability. The measurement is independent of the gas, and the technology is suitable for the particular gas species being measured.

A capacitance manometer utilizes two electrodes configured in a concentric arrangement on a ceramic disk, which is parallel to a thin, flat diaphragm. When the pressure on the diaphragm is equal, the diaphragm is flat and the bridge is balanced. Pressure deflects the diaphragm and the capacitance of the center electrode changes with respect to the outer electrode causing the bridge to become unbalanced, and generating a signal. This signal is amplified and demodulated to produce a useable, high level (0 to 5 or 10 VDC) output. The 0 to 5 volt signal is consistent with that used for thermal MFC. The capacitance technique has been shown to provide accuracy of 1% of reading for pressure ranging from 10E-05 Torr to 3000 psi.

B. *PMFC Configuration*

The flexibility of the PMFC allows for a wide variety of flow versus pressure configurations (Fig. 3). The objective is to minimize the PMFC's two pressure drop components, the valve and the control orifice, at full scale flow. This leads to maximum gas utilization.

For the control valve, two factors must be balanced. The first is to achieve minimum pressure drop across the valve at full scale flow and lowest inlet pressure. This is done by making the valve conductance (orifice) as large as possible. The second is to maintain the leakage rate across the valve to less than the minimum implant flow at the highest inlet pressure. This is important because closed valve leakage determines the minimum controllable flow. Valve leakage is reduced by making the valve orifice smaller. Balancing these factors results in a valve that has a pressure drop of 1 to 2 torr for flows on the order of 5 sccm.

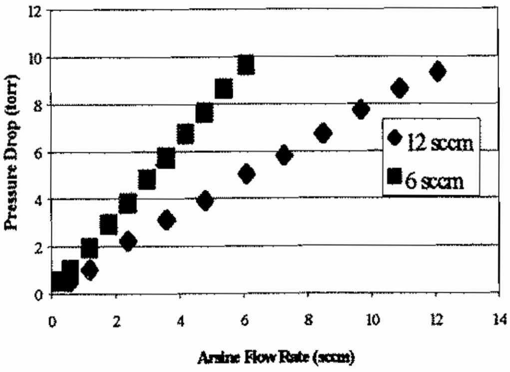

Fig. 3. Type 1640 Pressure Drop versus Flow

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Critical flow orifice sizing, to set up the linear relationship between pressure and flow, is straightforward. The maximum flow rate, control pressure (P1) and outlet pressure (P2) determine the orifice size and shape. The control pressure is typically set at a pressure of 4 to 10 torr as the outlet pressure is typically less than 5E-1 torr for ion implant applications. Once the control pressure is set, the orifice conductance, C, is established for the given full scale flow rate. An appropriate orifice shape and diameter are then determined.

IV. GAS CORRECTION FACTORS

MFC, both thermal and pressure based are most often calibrated with inert surrogate gases because many of the process gases are hazardous and/or corrosive. The use of surrogates requires that gas correction factors be used for both thermal and pressure based MFCs (Table I). The PMFC'S gas correction factor (SGCF) may be easily determined by the formula.

$$SGCF_{gasx} = \sqrt{\frac{(\gamma_{gasx}/M_{gasx})[2/(\gamma_{gasx}+1)^{(\gamma_{gasx}+1)/(\gamma_{gasx}-1)}]}{(\gamma_{gasy}/M_{gasy})[2/(\gamma_{gasy}+1)^{(\gamma_{gasy}+1)/(\gamma_{gasy}-1)}]}}$$

TABLE I
Gas Correction Factors

	Pressure Based	Thermal Based
Nitrogen (ref.)	1.0	1.0
AsH3	0.581	0.673
BF3	0.608	0.508
CF4	0.527	0.420
PH3	0.882	0.732
SiF4	0.480	0.348

V. UPSTREAM GAS PRESSURE EFFECTS

PMFC's are insensitive to inlet pressure effects. A change in inlet pressure is sensed by the manometer (Fig. 2). This change is automatically compensated by the control electronics and valve because pressure, P1 is adjusted to control flow. Thermal MFC'S are subject to an effect on the flow measurement accuracy as there are both static and dynamic pressure coefficients associated with the measurement device. The static coefficient varies from manufacturer to manufacturer and is on the order of 0.002% to 0.01% per psi. The dynamic coefficient depends on the rate of pressure change.

VI. DOWNSTREAM PRESSURE EFFECTS

The PMFC's configuration is based on the downstream pressure, desired gas flow rate and inlet gas pressure as discussed previously. For ion implantation the ion source pressure is on the order of 1E-4 torr and the PMFC's outlet pressure is generally below 5E-1 torr at full scale flow. There is little effect on the PMFC's ability to control flow over the 5 to 100% of full scale flow range because the outlet pressure drops as flow rate is reduced.

Increasing the downstream pressure by the addition of a co-gas, for example, can reduce the PMFC's ability to control low flows. The PMFC's critical flow relationship between pressure and flow applies only when the pressure upstream of the orifice is at least twice that downstream. Once the downstream pressure increases to above half the upstream control pressure the PMFC's flow will decrease.

Thermal MFC's are not affected by downstream pressure except when the sensor is located downstream. In this case there is a similar pressure coefficient as discussed in Section VI. Otherwise, the device pressure drop is maintained with the increase in minimum inlet pressure limited to the increase in downstream pressure.

VII. EMPTY BOTTLE DETERMINATION

The cylinder change-out decision for maximum gas utilization must be based on bottle pressure. Direct pressure measurement should be used to accurately determine bottle pressure. Pre-mature cylinder change-outs and aborted implants due to inadequate pressure for gas flow may be eliminated. This is important for both thermal and pressure based MFC capable of operating at pressures below 10 torr.

Alternative methods are available but they are not recommended for use in making decisions about changing out the SDS bottle.

A. *Direct Measurement*

A device such as a 1000 torr full scale capacitance manometer is appropriate as it covers the full useful range of the SDS bottle pressure from 1 to 1000 torr with a typical accuracy of 0.5% of reading. The output of this manometer should be compared to the full scale flow pressure drop of the device to generate appropriate implanter warning and interlock signals.

B. *Internal PMFC Baratron*

The Type 1640 PMFC can be used under static, no flow conditions, to sense SDS bottle pressure. It uses an internal Baratron capacitance manometer to measure the pressure that correlates to gas flow. The device's full scale pressure is set for full scale flow during calibration. The device output, flow, is proportional to pressure and thus can be used to measure bottle pressure.

To determine bottle pressure, shut the valve downstream of the PMFC and open the valve(s) upstream of the MFC. The flow output indicates the source gas bottle pressure. For example, consider an instrument that is sized for 5 sccm arsine flow at a full scale control pressure of 5 torr. Since the capacitance manometer's output is linear with pressure, a 6 sccm output would indicate at bottle pressure of approximately 6 torr. Type 1640's are set up so that if the bottle pressure is 120% of the control pressure, there is adequate pressure to achieve full scale flow. The limit to the pressure test is the configuration of the particular device's output that is limited to approximately 140% of full scale.

C. *Valve Voltage*

Valve voltage may be used to indirectly determine sufficient source gas pressure by an active flow test. When there is insufficient flow relative to the instrument's setpoint, the valve goes full open and there is a rapid change in valve voltage. This may be an indication of low pressure. The problem with using this voltage indication is that it can also be affected by changes in the valve such as clogging or other deterioration. This may cause the user to remove the SDS bottle when there is still useable gas instead of questioning the MFC. The degree of this voltage change is dependent on the supplier and valve type.

VIII. THERMAL BASED FLOW CONTROL

Thermal mass flow measurement utilizes a capillary (sensor) tube with heaters and temperature sensors arranged symmetrically on the outer surface. The ends of the tube are clamped both mechanically and thermally to the body of the instrument such that the thermal environment is symmetric about the center of the tube. Thus, any imbalance detected by the sensors is interpreted as a mass flow within the tube.

Thermal mass flow controller optimization for minimum pressure drop is dependent on the sensor tube and valve pressure drops. The valve pressure drop is similar to that of the PMFC. Sensor tube pressure drop depends on its temperature, diameter and length, gas and gas flow rate and pressure.

Thermal sensor configuration is essentially fixed for specific flow measurement requirements. Increasing the tube diameter, reducing tube length and/or bypassing flow to reduce sensor tube flow reduces pressure drop. All of the above decrease the flow signal to noise ratio. Increasing the energy (heat) transmitted to the sensor tube (and gas) can counteract this. The key is to remain below the decomposition temperatures of the gas. It has been reported that thermal MFC's can provide pressure drops of 10 torr with 5 sccm of nitrogen.

IX. FIELD TEST RESULTS

The need to improve gas utilization, particularly for BF_3 SDS, has required that instruments be configured for inlet pressures below 10 torr. PMFC's are now configured for pressures as low as 6 torr. These lower pressure differential models of the 1640 were provided to customers for evaluation and test in mid-1997.

Testing was done at a major semiconductor manufacturer on an Eaton GSD90E2 high current ion implanter with two Type 1640 devices to determine the impact of required inlet pressure on boron triflouride utilization. The control instrument (012) required a minimum inlet pressure of 11 torr while the experimental instrument (045) required only 6 torr at a full scale flow of 5 sccm. The experimental device showed a dramatic improvement in normalized, JY bottle lifetime (Table II).

TABLE II

PRODUCTIVITY DEPENDENCE ON DEVICE INLET PRESSURE

Type 1640 Model	012	045
F.S. Flow Rate	5 sccm	5 sccm
F.S. Inlet Pressure	11 torr	6 torr
F.S. Control Pressure	9 torr	4.3 torr
Wafers per Bottle*	11496	16313
Bottle Life*	22 days	31 days

X. SUMMARY

PMFC's, such as the MKS Type 1640, are capable of achieving maximum SDS source gas cylinder utilization for ion implantation because they offer the flexibility of being optimized by the appropriate selection of valve orifice and control pressure for a specific application.

Maximum cylinder utilization also depends on the accurate measurement of cylinder pressure. The capacitance measurement technique, such as the MKS Baratron, Type 722, has become widely accepted by users of SDS in implanters with both mass flow measurement techniques.

TABLE III.

COMPARISON OF THERMAL AND PRESSURE BASED MFC

Parameter	Type 1640 PMFC	Thermal MFC
Full Scale pressure drop (minimum)	6 torr	10 torr
Heat added to gas	No	Yes
Zero flow indication	No	Yes
Zero pressure indication	Yes	No
Direct SDS pressure indication	Yes	No
Indirect SDS pressure indication (valve voltage)	Yes	Yes
Flow independent of MFC inlet pressure	Yes	No
Flow dependent on downstream pressure	P1 < 2P2	No

ACKNOWLEGMENT

The authors wish to thank Joe Malenfant of IBM and Paul Lucas of MKS Instruments for their efforts in collecting the gas usage and pressure drop data provided herein.

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